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A NEW METHOD FOR CALCULATING WING ALONE AERODYNAMICS TO ANGLE OF ATTACK 180°

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FOREWORD

The work described in this report has been performed as a first step to allow extension of the Naval Surface Warfare Center (NSWCDD) Aeroprediction Code (APC) to encompass the full angle of attack (AOA) range of missiles during their flight. The 1993 version of the APC (AP93) was limited to AOA of 30 deg. While this covers the AOA range of many missiles, some configurations experience 35 to 40 deg AOA during flight and others can experience near 90 deg AOA at launch.

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ABSTRACT

A new semiempirical method has been developed to estimate wing alone aerodynamics at all Mach numbers and angles of attack (AOA) encountered in flight. The method utilizes the slender body or linearized theories at low AOA and several wing alone data bases at higher AOA. In areas where data is not available, extrapolations and interpolations are used with existing data. The new method is shown to be more accurate than the second-order technique developed for the 1993 version of the NSWCDD Aeroprediction Code (AP93) over the AOA range of 0 to 30 deg where that technique is applicable. More importantly, however, is the fact that the new method allows AOA to 180 deg. As a result, this new wing alone method forms the first step in expanding the AP93 to higher AOA than 30 deg.

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INTRODUCTION

Estimating missile aerothermodynamics over the flight regime where missiles fly is quite important in all phases of design. These aerodynamics are used by the flight dynamicist to estimate range performance and miss distance; the heating information is used to perform heat transfer analysis; and the aerodynamic and thermodynamic loads are used by the structural engineer to estimate structural integrity of the configuration. Missiles which are launched from a vertical launcher can experience angles of attack (AOA) approaching 90 deg if a strong crosswind is present. Missiles launched from aircraft undergoing maneuvers can also experience AOA approaching 60 deg. Finally, terminally guided missiles undergoing maneuvers in the end game can anticipate AOA as high as 40 deg. Hence, it is necessary to have aerodynamics estimates to at least 60 deg AOA to cover the flight regime for all possible conditions. Figure 1 is an operational envelope for an aeroprediction code which, hopefully, will cover all possible conditions for missiles.

The recent version of the NSWCDD Aeroprediction Code (AP93) released to the public[1-3] was limited in AOA to about 30 deg because the wing alone, wing-body, and body-wing interference aerodynamics were developed only up to about 30 deg AOA (dotted line in Figure 1). In some cases, the accuracy degraded at an AOA of 25 deg. One reason for this degradation was the second-order accuracy method derived for the wing alone solution. While this method gave much better estimates of wing aerodynamics than the linear theory of the 1981 version of the Aeroprediction Code (AP81)[4-6] above α of about 10 deg, it still failed for AOA greater than about 30 deg.

To understand why the second order method fails at $\alpha \geq 30$ deg, refer to Figures 2 and 3. Figure 2 considers AOA up to about 30 deg and examines the physical characteristics of the wing alone normal force as a function of aspect ratio and Mach number. This figure was the basis for the methodology described in References 1 through 3. In that methodology, the nonlinear wing alone term was modelled as a combination of aspect ratio, taper ratio, and Mach number.

As seen in Figure 2, at low to moderate values of aspect ratio typical of those used for most missiles, C_{N_α} will typically increase as AOA increases. This increase is larger with the smaller aspect ratio wings where the linear lift term is smallest (C_{N_α} approaches $\pi/2$ AR). At high aspect ratio where the linear lift term approaches its 2-D value of 2π, the nonlinear lift with AOA greater than about 10 to 15 deg is typically negative. In all cases, there is a noticeable effect of compressibility for large values of M_N. These two effects can be modelled reasonably well up to α of about 30 deg with a second-order technique. However, as seen in Figure 3, only the high aspect ratio wing alone lift curves could be

successfully modelled with a second-order technique. That is because the low to moderate aspect ratio planforms have a point of inflection where the slope of the C_N versus α curve changes sign. As a result, a second-order technique for estimating wing alone normal force will fail for these planforms at higher AOA and higher order mathematical models must be examined.

In examining the literature for high AOA semiempirical methods for wing alone aerodynamics, Fidler[4] developed a fourth order method in α versus a second order method which was used in References 1 through 3. However, Fidler's method had two fundamental problems. First he used the wing alone estimate of normal force at $\alpha = 0$, $\pi/2$, and π and the C_{N_α} conditions at $\alpha = 0$, $\pi/2$, and π. In using these conditions, inaccuracies occurred away from the end points due to a lack of information between $\alpha = 0$ and $\pi/2$, and $\alpha = \pi/2$ and π. The second problem with Fidler's method was that it was developed in the early 70's when not much wing alone data was available; hence, it was limited in Mach number and aspect ratio due to lack of data.

While Fidler's method does not give as accurate and generically applicable a technique as desired, it is the correct general approach for high AOA wing alone solutions. The method developed in this report is similar but much more accurate and robust. As such, it is believed to be the first accurate and robust wing alone semi-empirical method for estimating normal force over the entire AOA and Mach number range. Therefore, it is the first step in extending the AP93 code above AOA of 30 deg.

ANALYSIS

The nonlinear wing alone normal force coefficient model of Reference 1 is:

$$C_{N_W} = \left[\left(C_{N_\alpha}\right)_{\alpha=0} \alpha_W + K_1 \sin^2\alpha_W\right] \frac{A_W}{A_{ref}} \tag{1}$$

$\left(C_{N_\alpha}\right)_{\alpha=0}$ of Equation (1) is based primarily on linearized theories, and K_1 is an empirically derived constant as a function of M_∞, λ, AR, and M_N. As already discussed, this method works quite well up to $\alpha_W = 25$ to 30 deg. However, beyond that, a higher order prediction method is needed for many wing planforms. A more accurate method to estimate C_{N_W} is given by

$$C_{N_W} = a_0 + a_1 \alpha_W + a_2 \alpha_W^2 + a_3 \alpha_W^3 + a_4 \alpha_W^4 \tag{2}$$

α_W in both Equations (1) and (2) is defined as the AOA of the unperturbed free stream on the wing itself. That is

$$\alpha_W = | \alpha + \delta | \tag{3}$$

Here, only positive AOA (α_W) are considered since it is assumed that the missile wing planforms have no chamber and, as a result, the normal force at a negative AOA is simply the negative of that at the same positive value of AOA.

To predict the wing alone normal force using Equation (2) now requires that five constants be evaluated versus three for Equation (1). Since there are five constants, five independent equations or conditions are needed. The first condition has already been alluded to. That is, most missile lifting surface planforms are symmetric and have zero chamber. As a result, $(C_N)_{\alpha=0} = 0$ and, therefore, from Equation (2),

$$a_0 = 0 \tag{4}$$

Secondly, we will assume that at $\alpha = 0$, C_{N_α} can be estimated accurately enough by linearized theories. Once again, Equation (2) yields

$$a_1 = \left(C_{N_\alpha}\right)_{\alpha=0} \tag{5}$$

These values of $\left(C_{N_\alpha}\right)_{\alpha=0}$ are already available in the AP93 and are known to give reasonably accurate results for planforms where the thickness is not too large and AOA is fairly small.

To determine the remaining three conditions, several alternatives are available. The first alternative is to take advantage of the fact that at $\alpha = \pi/2$, $C_{N_\alpha} = 0$ since the C_{N_w} is a maximum at $\alpha = \pi/2$. Using this condition and two values of C_{N_w} at two different AOA, the remaining three constants can be determined. The question here is which two AOA to use. One set that warrants consideration is $\alpha_1 = \pi/6$ and $\alpha_2 = \pi/3$, since this divides the AOA range up into equal $\pi/6$ increments where the conditions are defined for evaluating the constants a_i.

Examining Figures 2 and 3, it is seen that a fairly strong nonlinearity occurs for $\alpha < 30$ deg for low aspect ratio wings. Hence, an argument could be made that a lower value of α would be more appropriate than $\alpha_1 = \pi/6$. Hence values of $\alpha_1 = 20$ deg and $\alpha_2 = 60$ deg, and $\alpha_1 = 20$ deg and $\alpha_2 = 45$ deg, can be used to compare the $\alpha_1 = 30$ deg and $\alpha_2 = 60$ deg predictions against.

A fourth option for defining the three remaining constants using the fourth order Equation (2) is to use three values of α versus using two values of α and the condition that $C_{N_\alpha} = 0$ at $\alpha = \pi/2$. Using the rationale of the strong nonlinearity below $\alpha = 30$ deg for low aspect ratio configurations and the fact $\alpha \leq 30$ deg is the most important part of the

AOA range, values of $\alpha_1 = 15$ deg, $\alpha_2 = 30$ deg, and $\alpha_3 = 60$ deg, seem appropriate. To provide more equal spacing between $\alpha_1 = 15$ deg and $\alpha_3 = 60$ deg, yet focus more on the $\alpha = 0$ to 30 deg range, another alternative for α_2 is 35 deg. Above $\alpha = 60$ deg, approximate equations can be used to extend the C_{N_w} from $\alpha = 60$ deg to $\alpha = 90$ deg.

Each of the five alternatives outlined in the previous discussion for computing the three coefficients a_2, a_3, and a_4 of Equation (2) will require three different sets of equations. Each of these alternative sets of equations will be defined separately. Taking the first condition first, that is $(C_{N_\alpha})_{\alpha=\pi/2} = 0$, we find upon taking the derivative of Equation (2) and substituting this condition in yields:

$$a_2 + 2.356\,a_3 + 4.935\,a_4 = -.318\,a_1 \tag{6}$$

The other two conditions that compliment Equation (6) must come from experimental data. Utilizing condition (4), Equation (2) can be written for these two conditions as:

$$C_{N_1} = a_1\,\alpha_1 + a_2\,\alpha_1^2 + a_3\,\alpha_1^3 + a_4\,\alpha_1^4 \tag{7}$$

$$C_{N_2} = a_1\,\alpha_2 + a_2\,\alpha_2^2 + a_3\,\alpha_2^3 + a_4\,\alpha_2^4 \tag{8}$$

Note that in Equations (7) and (8) the subscript W has been dropped for simplicity so that α_1, α_2 are understood to mean the α_W of the wing at conditions one and two. Likewise, C_{N_1} and C_{N_2} are understood to mean the normal force coefficient of the wing alone at the total AOA as defined by

$$(\alpha_W)_1 = \alpha_1 = (\alpha + \delta)_1 \tag{9}$$

$$(\alpha_W)_2 = \alpha_2 = (\alpha + \delta)_2 \tag{10}$$

Equations (6), (7), and (8) can be solved simultaneously for a_2, a_3, and a_4 in terms of known quantities. The solutions are given in Equations (11) through (13).

$$a_4 = \frac{1}{\left(\dfrac{\alpha_2^2 - 4.935}{\alpha_2 - 2.356}\right) - \left(\dfrac{\alpha_1^2 - 4.935}{\alpha_1 - 2.356}\right)} \left[\frac{C_{N_2}/\alpha_2^2 - a_1/\alpha_2 + .318\,a_1}{\alpha_2 - 2.356} - \frac{C_{N_1}/\alpha_1^2 - a_1/\alpha_1 + .318\,a_1}{\alpha_1 - 2.356}\right] \tag{11}$$

$$a_3 = \frac{C_{N_1}/\alpha_1^2 - a_1/\alpha_1 + .318\,a_1}{\alpha_1 - 2.356} - \left(\frac{\alpha_1^2 - 4.935}{\alpha_1 - 2.356}\right) a_4 \tag{12}$$

$$a_2 = -.318\,a_1 - 2.356\,a_3 - 4.935\,a_4 \tag{13}$$

Equations (11), (12), and (13) give the values of a_2, a_3, and a_4 in terms of the known parameter a_1 from the aeroprediction code and the chosen parameters, α_1 and α_2. Once α_1 and α_2 are chosen, C_{N_1} and C_{N_2} can be found from a three-parameter interpolation of the wing alone data bases where the parameters are AR, λ, and M_∞.

The first conditions chosen for α_1 and α_2 are $\alpha_1 = \pi/6$ and $\alpha_2 = \pi/3$. Substituting these values of α_1 and α_2 into Equations (11) through (13) there is obtained:

$$a_2 = -3.40\,a_1 + 10.10\,(C_N)_{\alpha=30^\circ} - 1.90\,(C_N)_{\alpha=60^\circ} \tag{14}$$

$$a_3 = 3.37\,a_1 - 15.01\,(C_N)_{\alpha=30^\circ} + 4.56\,(C_N)_{\alpha=60^\circ} \tag{15}$$

$$a_4 = -.98\,a_1 + 5.12\,(C_N)_{\alpha=30^\circ} - 1.79\,(C_N)_{\alpha=60^\circ} \tag{16}$$

While Equations (14) through (16) give values of a_2, a_3, and a_4 based on equally spaced intervals in α between 0 and $\pi/2$, it may not be the best choice for accuracy. In examining the C_N versus α curves of References 5 through 7, it is seen that for low aspect ratio wings at both low and high Mach number, a large amount of nonlinearity occurs between $\alpha = 0$ and $\pi/6$. Hence, picking a point in this range may improve the accuracy. Secondly, many of the C_N versus α curves have a point of inflection between $\alpha = 0$ and $\pi/4$. To pick a point at $\alpha = \pi/6$ and $\pi/3$ may not accurately account for this change in curvature of the C_N versus α curve. Finally, while the method is applicable for $\alpha = 0$ to $\pi/2$, the largest number of applications is for $\alpha = 0$ to 50 deg. For these reasons, two other sets of values of α_1 and α_2 have been chosen. These values were chosen to address the concerns just discussed. A comparison of the accuracy of the three sets of values can then be made and the best set chosen based on data comparison.

Substituting $\alpha_1 = 20$ deg $= .349$ rad and $\alpha_2 = 45$ deg $= .785$ rad into Equations (11) through (13) there is obtained:

$$a_2 = -4.65\,a_1 + 17.96\,(C_N)_{\alpha=20^\circ} - 2.10\,(C_N)_{\alpha=45^\circ} \tag{17}$$

$$a_3 = 5.78\,a_1 - 32.03\,(C_N)_{\alpha=20^\circ} + 7.05\,(C_N)_{\alpha=45^\circ} \tag{18}$$

$$a_4 = -1.88\, a_1 + 11.65 \left(C_N\right)_{\alpha = 20°} - 2.94 \left(C_N\right)_{\alpha = 45°} \tag{19}$$

Note that Equations (14) through (16) and (17) through (19) require values of C_N at values of α_1 of 30 deg and 20 deg, respectively, and values of α_2 of 60 deg and 45 deg, respectively. These values are found from the data bases of References 5 through 7. These data will allow the direct calculation of C_{N_1} and C_{N_2} for most wing planforms. For wing planforms where a complete data base is not available (e.g., AR = 4.0, λ = 0, and 1.0) interpolation or extrapolation of these data bases is required.

For values of α_1 = 20 deg and α_2 = 60 deg, Equations (11) through (13) become:

$$a_2 = -4.355\, a_1 + 15.107 \left(C_N\right)_{\alpha = 20°} - 0.933 \left(C_N\right)_{\alpha = 60°} \tag{20}$$

$$a_3 = 4.780\, a_1 - 22.439 \left(C_N\right)_{\alpha = 20°} + 3.126 \left(C_N\right)_{\alpha = 60°} \tag{21}$$

$$a_4 = -1.464\, a_1 + 7.651 \left(C_N\right)_{\alpha = 20°} - 1.304 \left(C_N\right)_{\alpha = 60°} \tag{22}$$

For the cases where three AOA are chosen to define normal force coefficients to evaluate the coefficients a_2, a_3, and a_4, Equations (11), (12), and (13) are replaced by:

$$\begin{aligned} a_4 = {} & \frac{1}{(\alpha_3 - \alpha_2)(\alpha_3 - \alpha_1)} \left[\frac{1}{\alpha_3^2} \left(C_{N_3} - a_1\, \alpha_3\right) - \frac{1}{\alpha_2^2} \left(C_{N_2} - a_1\, \alpha_2\right) \right] \\ & - \frac{1}{\alpha_2 - \alpha_1)\ (\alpha_3 - \alpha_1)} \left[\frac{1}{\alpha_2^2} \left(C_{N_2} - a_1\, \alpha_2\right) - \frac{1}{\alpha_1^2} \left(C_{N_1} - a_1\, \alpha_1\right) \right] \end{aligned} \tag{23}$$

$$a_3 = -a_4\ (\alpha_3 + \alpha_2) + \frac{1}{(\alpha_3 - \alpha_2)} \left[\frac{1}{\alpha_3^2} \left(C_{N_3} - a_1\, \alpha_3\right) - \frac{1}{\alpha_2^2} \left(C_{N_2} - a_1\, \alpha_2\right) \right] \tag{24}$$

$$a_2 = \frac{1}{\alpha_2^2} \left(C_{N_2} - a_1\, \alpha_2\right) - a_3\, \alpha_2 - a_4\, \alpha_2^2 \tag{25}$$

Substituting α_1 = 15 deg, α_2 = 30 deg, and α_3 = 60 deg (in radians) into Equations (23) through (25) there is obtained:

$$a_2 = 38.907 \left(C_N\right)_{\alpha = 15°} - 7.295 \left(C_N\right)_{\alpha = 30°} + .304 \left(C_N\right)_{\alpha = 60°} - 6.685\, a_1 \tag{26}$$

$$a_3 = -111.461 \left(C_N\right)_{\alpha = 15^\circ} + 34.832 \left(C_N\right)_{\alpha = 30^\circ} - 1.742 \left(C_N\right)_{\alpha = 60^\circ} + 12.767\, a_1 \tag{27}$$

$$a_4 = 70.959 \left(C_N\right)_{\alpha = 15^\circ} - 26.609 \left(C_N\right)_{\alpha = 30^\circ} + 2.217 \left(C_N\right)_{\alpha = 60^\circ} - 6.966\, a_1 \tag{28}$$

Finally, substituting $\alpha_1 = 15$ deg, $\alpha_2 = 35$ deg, and $\alpha_3 = 60$ deg into Equations 23 through 25, one obtains:

$$a_2 = 34.044 \left(C_N\right)_{\alpha = 15^\circ} - 4.824 \left(C_N\right)_{\alpha = 35^\circ} + 0.426 \left(C_N\right)_{\alpha = 60^\circ} - 6.412\, a_1 \tag{29}$$

$$a_3 = -88.240 \left(C_N\right)_{\alpha = 15^\circ} + 23.032 \left(C_N\right)_{\alpha = 35^\circ} - 2.322 \left(C_N\right)_{\alpha = 60^\circ} + 11.464\, a_1 \tag{30}$$

$$a_4 = 53.219 \left(C_N\right)_{\alpha = 15^\circ} - 17.595 \left(C_N\right)_{\alpha = 35^\circ} + 2.661 \left(C_N\right)_{\alpha = 60^\circ} - 5.971\, a_1 \tag{31}$$

To evaluate Equations (14) through (16), (17) through (19), (20) through (22), (26) through (28), and (29) through (31) requires tables of data for $\alpha = 15, 20, 30, 35, 45$, and 60 deg. These data are given in Tables 1 through 6 based on the data bases of References 5 through 7. To form Tables 1 through 6 required plots of C_{N_w} versus Mach number for each value of α noted above and for each wing aspect and taper ratio. In general, a great deal of consistency exists between the data bases at the lower values of AOA. However, as AOA increased above $\alpha = 30$ deg, there were some inconsistencies in the data bases as well as some gaps. To fill the gaps, plots were made of C_{N_w} versus aspect ratio for a given taper ratio and Mach number, and engineering judgement was exercised in making consistent data sets.

It is fair to say that even though the data bases of References 5 through 7 are extensive, additional wing alone data is needed at low Mach numbers ($M_\infty \leq 1.2$) and AOA greater than 30 deg, and at all Mach numbers for aspect ratio 4 and $\lambda = 0$ and 1.0.

As an example of the way Tables 1 through 6 were formed, consider Figures 4 through 7. They give C_{N_w} as a function of Mach number for various values of aspect and taper ratio for the case $\alpha_W = 30$ deg. Note that the three data base points are shown on the figures. For this AOA, there is a reasonable amount of consistency in the data for most conditions where data is available. The lines in the figures represent data that is included in Table 3. Data for the other tables was obtained in a comparable manner.

In analyzing Figures 4 through 7, it is seen that, in some cases, one data base was relied upon more than another.

The reason for this decision goes back to the way the data were taken for the three data sets. Reference 5 data was taken on a full wing planform at $1.6 \leq M \leq 4.63$. Measurements of pressure on the wing planforms were actually taken at many points on the wing and these values then integrated to obtain lift. This meant the thickness of the wings

was larger than most practical wing planforms due to all the pressure taps and lines inside the wing. This was particularly true for the larger values of λ where the root thickness was higher. It is suspected that this increased thickness contributed to a slightly lower value of normal force for some cases of Reference 5 compared to Reference 6. Reference 6 data was taken on fairly thin wings mounted on a splitter plate. This meant that only half the wing was used in the wind tunnel which, apparently, resulted in some fictitious stall results at higher AOA. At these conditions, the Reference 5 data was relied on primarily. Finally, the Reference 7 data base was made primarily from a combination of the References 5 and 6 data along with other available data. The Reference 7 data is important in comparing the References 5 and 6 data and in helping make a decision between the References 5 and 6 data bases on occasion.

In general, it was fairly easy to form the curves shown in Figures 4 through 7 for $\alpha \leq 30$ deg due to a reasonable amount of consistency in the data. It was also fairly easy to form the curves and tables for α_W up to 60 deg and $M \geq 1.6$ due to the fairly thorough data base of Reference 5. However, for $M \leq 1.2$ and $\alpha > 30$ deg, considerable judgement had to be used. Also plots of C_{N_w} versus aspect ratio for a given M_∞ and λ were made along with C_{N_w} versus α_W for a given AR, λ, and M_∞. Examples of these plots are given in Figures 8 and 9. Figure 8 gives C_{N_w} versus aspect ratio for $M_\infty = 0.8$ and $\lambda = 0.5$, and helps make sure the values in Tables 1 through 6 are smooth with respect to aspect ratio. Figure 9 gives C_{N_w} versus α_W for $AR = 0.5$, $\lambda = 0$, and $M_\infty = 0.8$. Note the curve selected above $\alpha = 40$ deg does not go through either data set from Reference 6 or 7.

Two other points need to be considered before completion of the analysis section. These have to do with normal force of the wing alone for $\alpha > 90$ deg for any of the methods presented previously, and normal force of the wing alone for the methods where three values of α were selected for determining the coefficients a_2, a_3, and a_4. For the latter problem, no condition was taken for C_{N_α} at $\alpha = \pi/2$ and the maximum AOA chosen for the normal force tables was at $\alpha = 60$ deg. Hence, it could be anticipated that erroneous results could be expected for 60 deg $< \alpha \leq 90$ deg in some cases. To remedy this situation, some approximate formulas have been developed for this AOA range that are more consistent with the trends of the data in References 5 through 7. Since data is available for most wing planforms at $\alpha = 60$ deg, the formulas use this value and basically extrapolate from it. The overall method is given in Figure 10.

The other problem mentioned is that for $\alpha > 90$ deg. For AOA greater than 90 deg, we define an AOA α^* by

$$\alpha = \pi/2 + \alpha^* \tag{32}$$

where α^* is the value of α greater than $\pi/2$. Then, from symmetry considerations

$$\left(C_{N_W}\right)_{\alpha = \pi/2 + \alpha^*} = \left(C_{N_W}\right)_{\alpha = \pi/2 - \alpha^*} \tag{33}$$

A summary of the wing alone fourth-order estimation process is as follows:

a) Select one of the five fourth-order techniques for computing the coefficients a_2, a_3, and a_4

b) Depending on the method selected, use the appropriate tables to compute the values of C_{N_1} and C_{N_2} (and C_{N_3} if methods 4 or 5 are selected) for the wing in question and at the Mach number of interest. Linear interpolation between the tables should be adequate.

c) Compute the value of a_1 from the aeroprediction code or another method as desired.

d) Use the appropriate set of Equations (14) through (16), (17) through (19), (20) through (22), (26) through (28), or (29) through (31), depending on which of the five methods were selected to compute a_2, a_3, and a_4.

e) Knowing a_0, a_1, a_2, a_3, and a_4, use Equation (2) to compute C_{N_w} of the wing for the given total AOA of the wing.

f) If method 4 or 5 is chosen and 60 deg $< \alpha_W <$ 90 deg, use equations in Figure 10 to compute value of C_{N_w} at appropriate α and M.

g) If $\alpha_W >$ 90 deg, use Equation (33) to compute value of C_{N_w}.

These five methods discussed previously will be compared in the next section and the best method will be chosen for incorporation into the aeroprediction code based on average percent errors compared to data.

RESULTS AND DISCUSSION

Results of wing alone normal force computations using the methods described in the preceding sections are shown in Tables 7 through 16. For purposes of identification, AP93 refers to the second-order technique used in the current version of the NSWCDD Aeroprediction Code. AP3060, AP2045, and AP2060 refer to the fourth-order schemes which rely on only two reference values of C_{N_w} for their solutions. As the designations imply, AP3060 uses reference points of 30 and 60 deg, AP2045 uses reference points of 20 and 45 deg, and AP2060 uses reference points of 20 and 60 deg. The fourth-order schemes using three reference points of 15,30,and 60 deg or 15,35, and 60 deg are identified as AP153060 and AP153560, respectively. Results are also shown in the tables from the experimental data bases of References 5 through 7 for each case where it was available. It should be reiterated that in many instances, the data values represent extrapolations, averages, or best-guess estimates based on engineering judgement.

Tables 7, 8, and 9 present the results for wings of aspect ratio 0.5 and taper ratios of 1.0, 0.5, and 0.0, respectively. Tables 10 through 12 and 13 through 15 show results for wings of aspect ratio 1.0 and 2.0, respectively, for the same taper ratios. Results for aspect ratio 4.0 wings are shown in Table 16 for the single taper ratio of 0.5 since this was the only combination for which data was available. In all cases, computations were performed for Mach numbers of 0.8, 1.2, 2.0, and 4.5. AP93 data is shown only up to 30 deg AOA since it was only intended to cover this range. AP3060, AP2045, and AP2060 solutions were computed up to 60 deg AOA while AP153060 and AP153560 solutions were extended up to 90 deg AOA using the extrapolation techniques described in Figure 9.

In the AP153060 and AP153560 results for low aspect ratio and low Mach number conditions, identical C_{N_w}'s may be found for AOA between 30 and 60 deg. This situation arises because the nature of the polynomial fits in this region is such that C_{N_w}'s greater than those at 60 deg AOA are generated at lower incidence angles. Since these solutions are not physically plausible, these C_{N_w}'s are replaced by the $\alpha = 60$ deg values. This procedure was found to give lower errors than an interpolation between the $\alpha = 30$ and $\alpha = 60$ deg reference points.

While an inspection of Tables 7 through 16 will provide detailed comparisons of individual results, a summary of the overall errors involved in each of the approximation schemes would be more useful as an evaluation tool. Tables 17 through 20 present such error values for the aspect ratios of 0.5, 1.0, 2.0, and 4.0, respectively. Within each of these tables, for a given taper ratio and Mach number, the error value shown is the rms error, in percent, taken over the AOA range. The numbers without parentheses were obtained by considering α's only up to 30 deg. Since AP93 results are valid only within this range, it is these values which offer a comparison of the new techniques to the old methodology. In instances where error values are shown in parentheses, comparison data was available up to $\alpha = 60$ deg and these numbers represent the averages over the entire AOA range from 10 to 60 deg. As can be seen from the tables, the new techniques do a good job in most cases, but the two reference point formulations (AP3060, AP2045, AP2060) give inferior results, relative to the three reference point methods (AP153060, AP153560) for low aspect ratio, low Mach number conditions. This situation arises primarily because of the inability of the two point methods to provide adequate resolution of the low AOA region where the lift curve slope is changing rapidly. The AP153060 and AP153560 methods were introduced in hopes of providing better coverage of the entire AOA range. The results indicate that this is indeed the case.

In order to provide a more readily apparent measure of the global performance of all of the methods, the errors were further averaged. Table 21 shows percent error values for each aspect ratio. These numbers were obtained by averaging over Mach number and taper ratio for each aspect ratio. Finally, Table 22 gives the weighted average of the error for each method over the entire range of comparison cases. As can be seen, all of the fourth-order methods, except AP3060, perform better than the current AP93 second-order approach in the 10 to 30 deg AOA range. The AP153060 method gives the best results, followed closely by AP153560. Over the extended AOA range from 10 to 60 deg, AP153560 gives the best results as indicated by the numbers in parentheses. Since AP153560 also reduced

some large errors in the AOA range near 40 deg, it was chosen as the method for integration into the Aeroprediction Code.

Figures 11 through 24 present plots of wing alone normal force coefficients versus AOA as computed by both AP93 and AP153560. Reference data points are also included. All plots are for taper ratios (λ) of 0.5. Figures 11 through 14 show the results for aspect ratio 0.5 computations at Mach numbers of 0.8, 1.2, 2.0, and 4.5, respectively. Figures 15 through 18 and 19 through 22 show results of these same Mach numbers for aspect ratios of 1.0 and 2.0, respectively. Figures 23 and 24 contain aspect ratio 4.0 information for Mach numbers of 2.0 and 4.5. No data points were available at the lower Mach numbers for this aspect ratio. As can be seen from these plots, AP153560 does as well, or better, than AP93 for AOA up to 30 deg. In addition, it does a good job of matching data points in the AOA range from 30 to 60 deg. The slight "kinks" which occur in some AP153560 curves at 60 deg AOA are caused by the extrapolation procedure employed for high α computations. There are also slight irregularities in some low Mach number results between 40 and 60 deg AOA. These are the result of the extreme sensitivity of the predicted normal force results to the reference values used at $\alpha = 35$ deg. Since these values are largely extrapolations, some uncertainties are introduced in this region. There is also a tendency for the approximating polynomial to produce an inflection point in this AOA range. This behavior could possibly be improved by using a smoothing function.

SUMMARY

A new fourth-order semiempirical method has been developed to estimate wing alone aerodynamics at all Mach numbers and AOA. The method utilizes the linearized theory approaches of the AP93 along with wing alone data bases to evaluate constants needed in the fourth-order equation. In comparing the new technique to data and the AP93, the new method not only gave aerodynamics over the entire AOA range but, on average, was more accurate than the AP93 method in the range of $0 \leq \alpha \leq 30$ deg .

In deriving the new method, many extrapolations were needed at low Mach numbers and high aspect ratio where either data was lacking or the data available had questionable accuracy. As a result, additional accurate wing alone wind tunnel data is needed for: 1) AR = 4.0; $\lambda = 0$, 1.0 at all Mach numbers and 2) $M < 1.5$, $\alpha > 30$ deg, and all aspect ratios. This additional data would allow the present method to be fine tuned and eliminate the extrapolations in the technique.

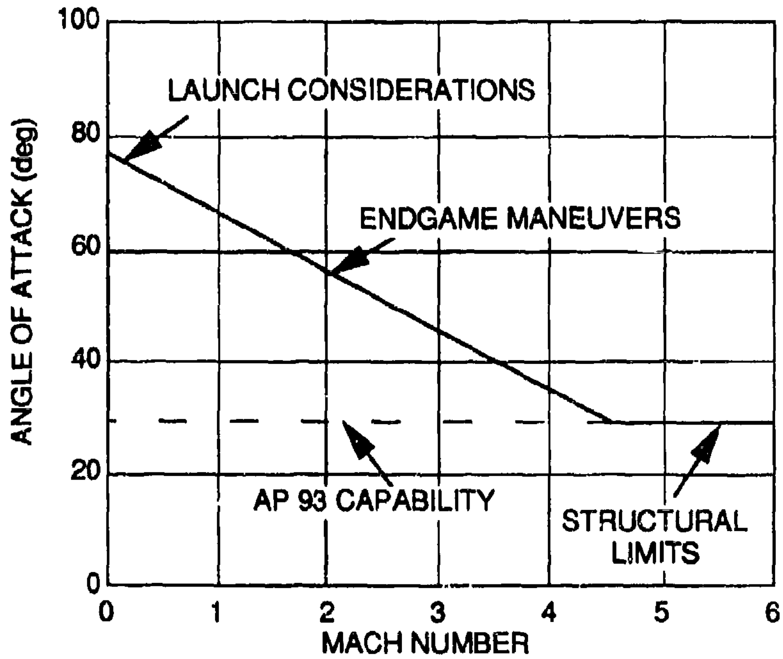

FIGURE 1. DESIRED OPERATIONAL ENVELOPE FOR AEROPREDICTION CODE VERSUS AP93 CAPABILITY

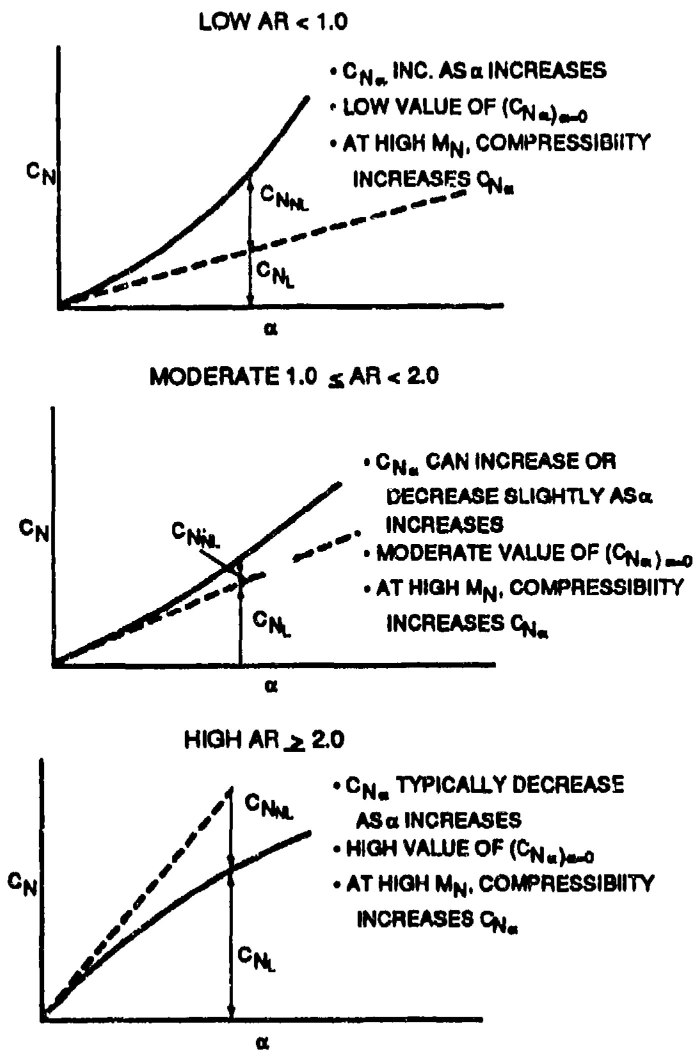

FIGURE 2. QUALITATIVE CHARACTERISTICS OF NORMAL FORCE COEFFICIENT OF WING ALONE AT AOA UP TO ABOUT 30°

REGION	C_{N_α} CHARACTERISTICS
A	• CAN BE ± DEPENDING ON AR • POINT OF INFLECTION MAY OCCUR ABOVE $\alpha = 25$ deg
B	• POINT OF INFLECTION TYPICALLY OCCURS FOR LOW TO MODERATE AR. NO POINT OF INFLECTION FOR HIGHER AR
C	• C_{N_α} TYPICALLY NEGATIVE • $C_{N_\alpha} = 0$ AT $\alpha = 90$ deg
D	• MIRROR IMAGE OF REGIONS A, B, C

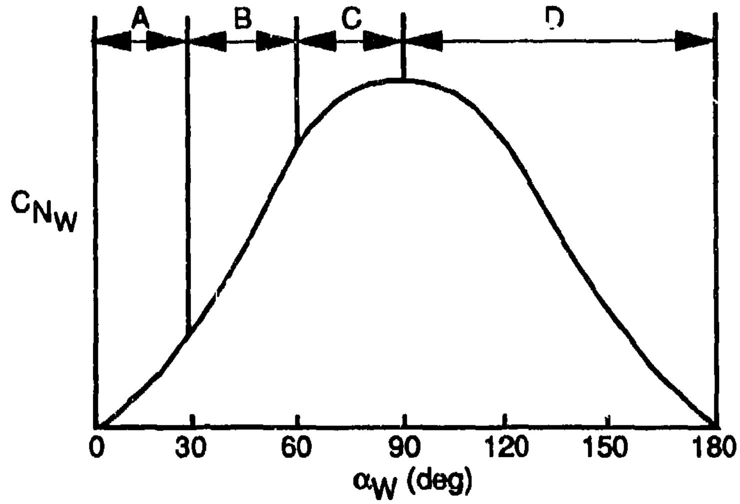

FIGURE 3. QUALITATIVE CHARACTERISTICS OF NORMAL FORCE COEFFICIENT OF WINGS ALONE AT ALL AOA

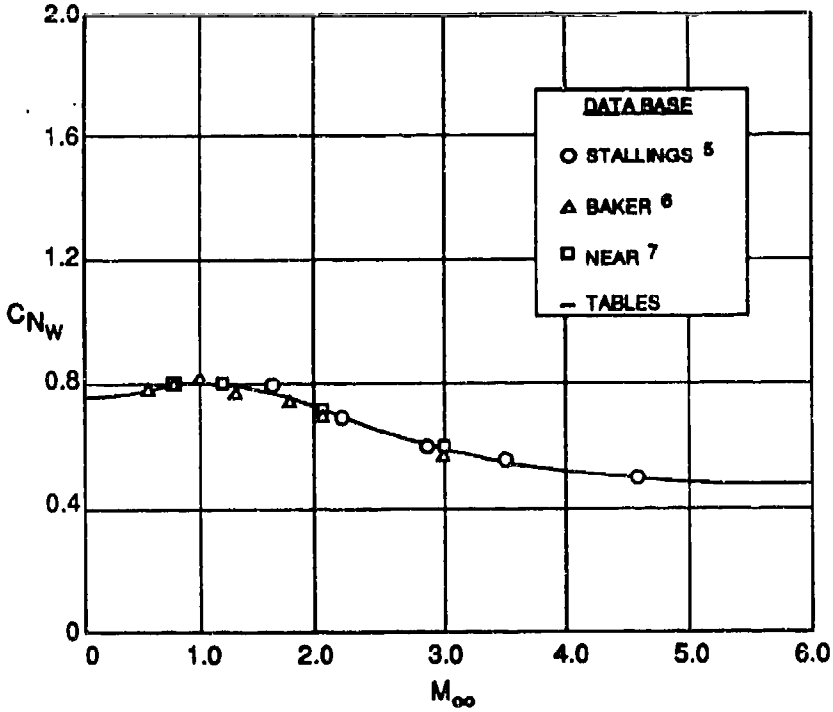

FIGURE 4a. WING ALONE NORMAL FORCE COEFFICIENT AS A FUNCTION OF MACH NUMBER (AR $\leq$ .5, λ = 0, α = 30°)

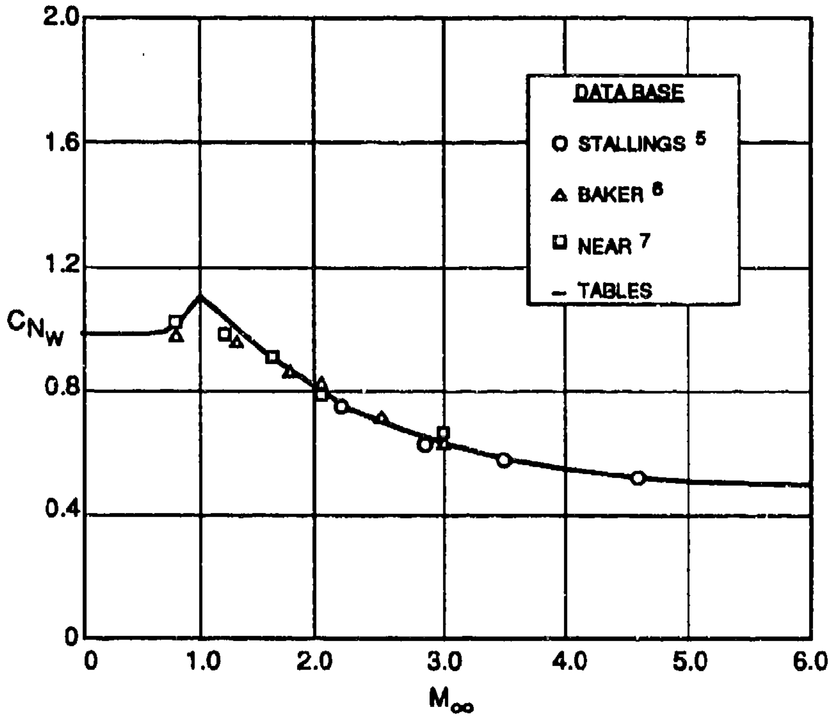

FIGURE 4b. WING ALONE NORMAL FORCE COEFFICIENT AS A FUNCTION OF MACH NUMBER (AR $\leq$ .5, λ = .5, α = 30°)

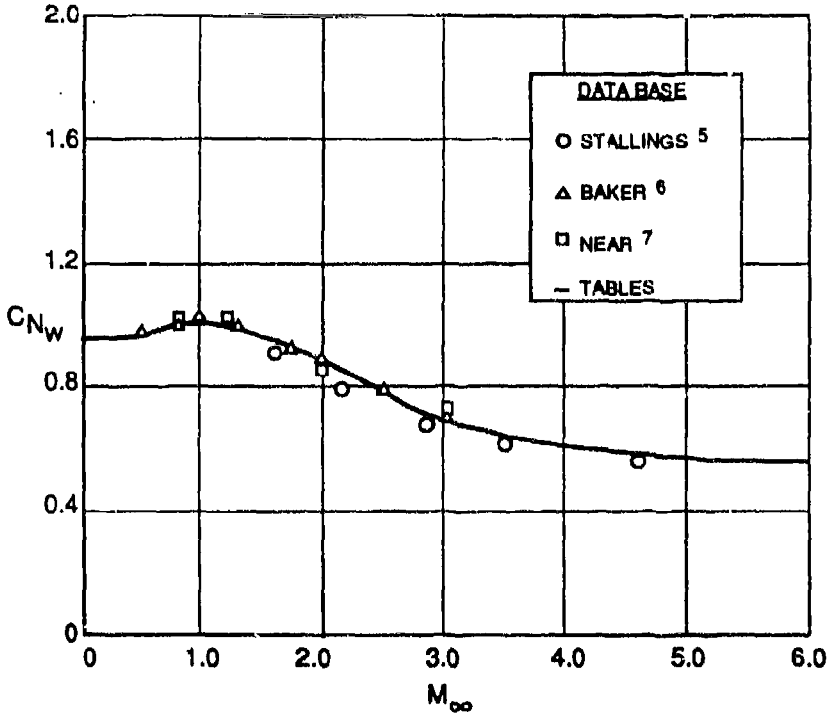

FIGURE 4c. WING ALONE NORMAL FORCE COEFFICIENT AS A FUNCTION OF MACH NUMBER (AR $\leq$ .5, λ = 1.0, α = 30°)

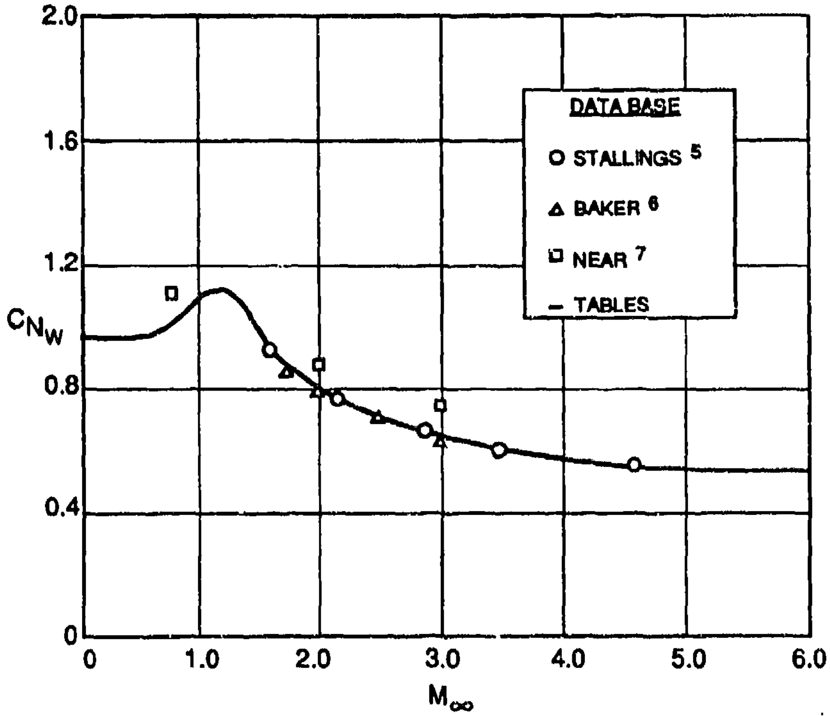

FIGURE 5a. WING ALONE NORMAL FORCE COEFFICIENT AS A FUNCTION OF MACH NUMBER (AR = 1.0, λ = 0, α = 30°)

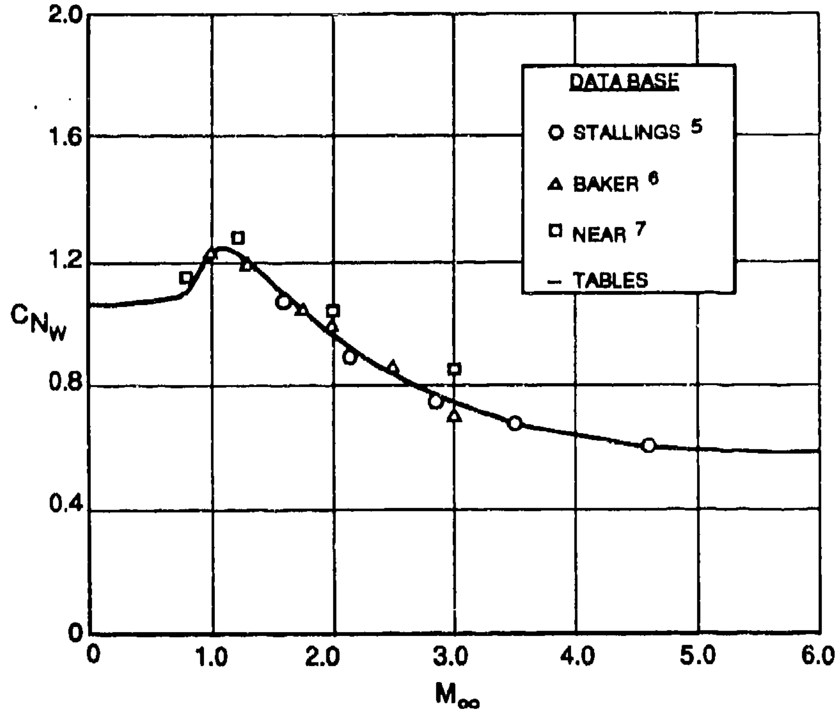

FIGURE 5b. WING ALONE NORMAL FORCE COEFFICIENT AS A FUNCTION OF MACH NUMBER (AR = 1.0, λ = .5, α = 30°)

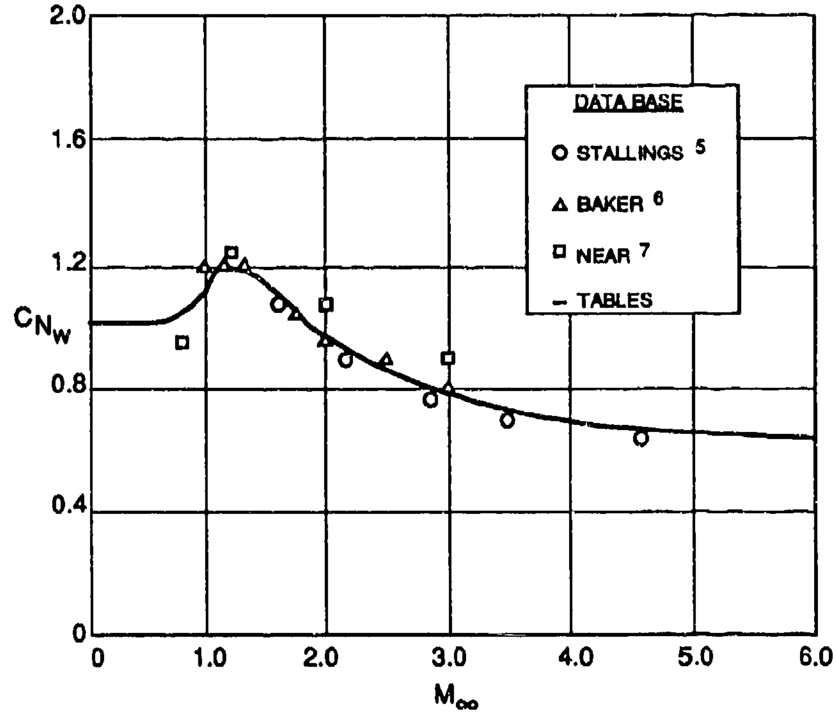

FIGURE 5c. WING ALONE NORMAL FORCE COEFFICIENT AS A FUNCTION OF MACH NUMBER (AR = 1.0, λ = 1.0, α = 30°)

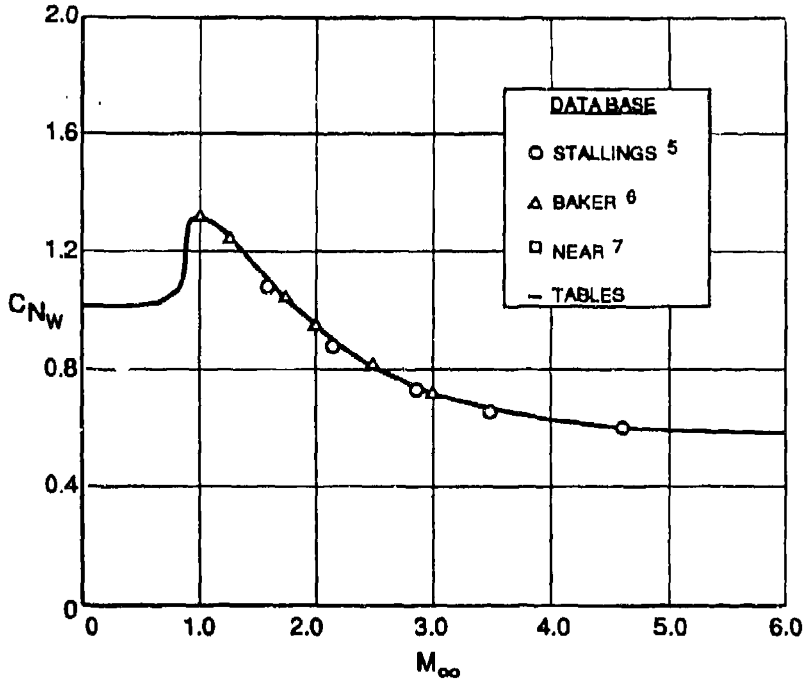

FIGURE 6a. WING ALONE NORMAL FORCE COEFFICIENT AS A FUNCTION OF MACH NUMBER (AR = 2.0, λ = 0, α = 30°)

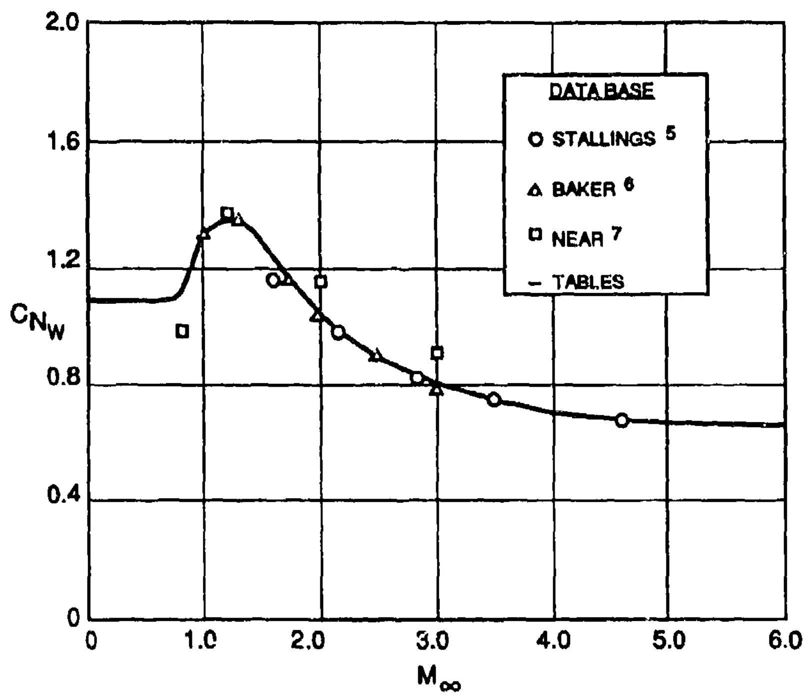

FIGURE 6b. WING ALONE NORMAL FORCE COEFFICIENT AS A FUNCTION OF MACH NUMBER (AR = 2.0, λ = .5, α = 30°)

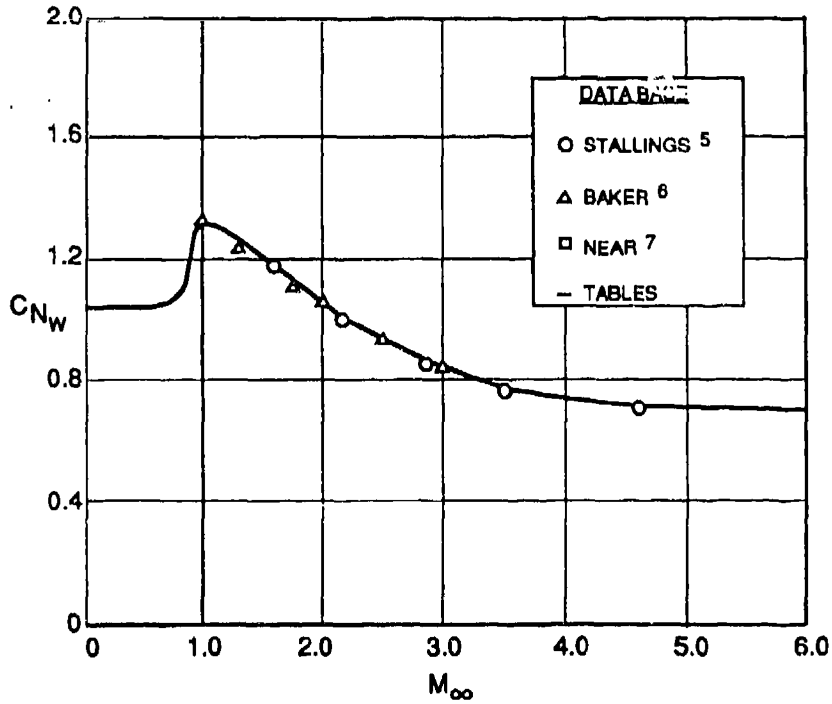

FIGURE 6c. WING ALONE NORMAL FORCE COEFFICIENT AS A FUNCTION OF MACH NUMBER (AR = 2.0, λ = 1.0, α = 30°)

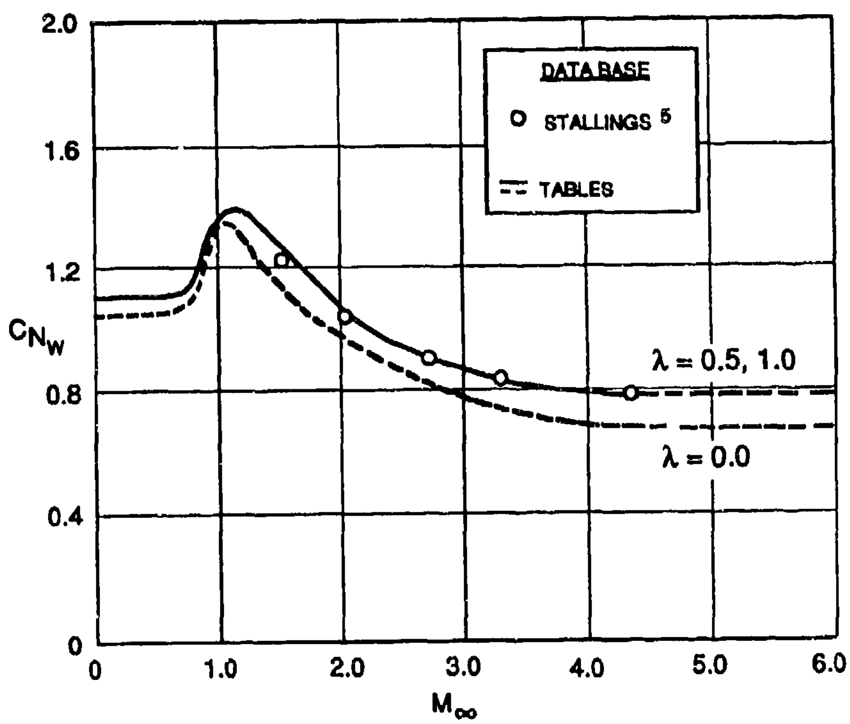

FIGURE 7. WING ALONE NORMAL FORCE COEFFICIENT AS A FUNCTION OF MACH NUMBER (AR = 4.0, λ = 0, .5, 1.0, α = 30°)

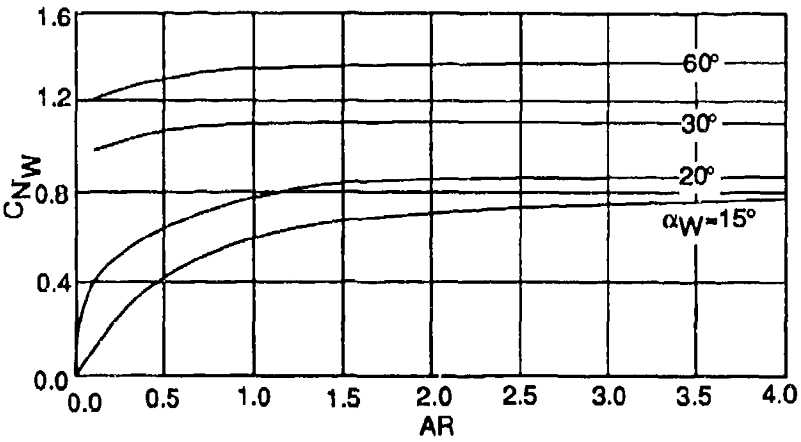

FIGURE 8. WING ALONE NORMAL FORCE COEFFICIENT AS A FUNCTION OF ASPECT RATIO AND ANGLE OF ATTACK
(M_∞ = 0.8, λ = 0.5)

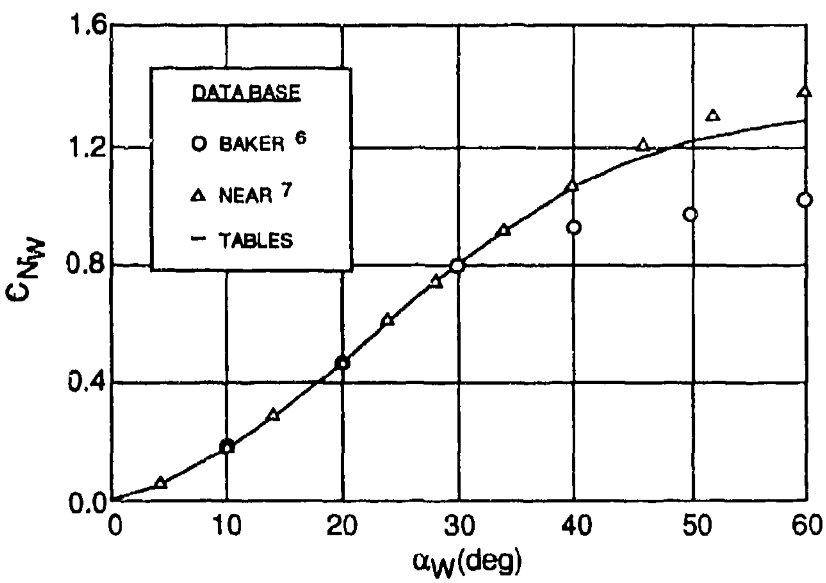

FIGURE 9. WING ALONE NORMAL FORCE COEFFICIENT AS A FUNCTION OF ANGLE OF ATTACK
(M_∞ = 0.8, AR = 0.5, λ = 0.5)

(a)

$$\frac{\text{For } M_\infty \geq 2.0;\ 60° < \alpha_W \leq 90°}{C_{N_w} = (C_{N_w})_{\alpha_w = 60°} \left[\frac{\sin \alpha_W}{\sin 60°} \right]}$$

(b)

$$\frac{\text{For } M_\infty \leq 1.2;\ 60° < \alpha_W \leq 90°}{C_{N_w} = (C_{N_w})_{\alpha_w = 60°} \left[\frac{\sin \alpha_W}{\sin 60°} \right]^{1/3}}$$

(c)

$$\text{For } 1.2 < M_\infty < 2.0;\ 60° < \alpha_W \leq 90°$$

Extrapolate between values at $M = 1.2$ and 2.0

$$C_{N_w} = \left(C_{N_w}\right)_{M = 1.2} + \left[\left(C_{N_w}\right)_{M = 2.0} - \left(C_{N_w}\right)_{M = 1.2}\right] \frac{(M - 1.2)}{0.8}$$

FIGURE 10. WING ALONE MODEL FOR α_W > 60 DEG WHEN THREE DATA SETS FOR C_{N_w} ARE CHOSEN

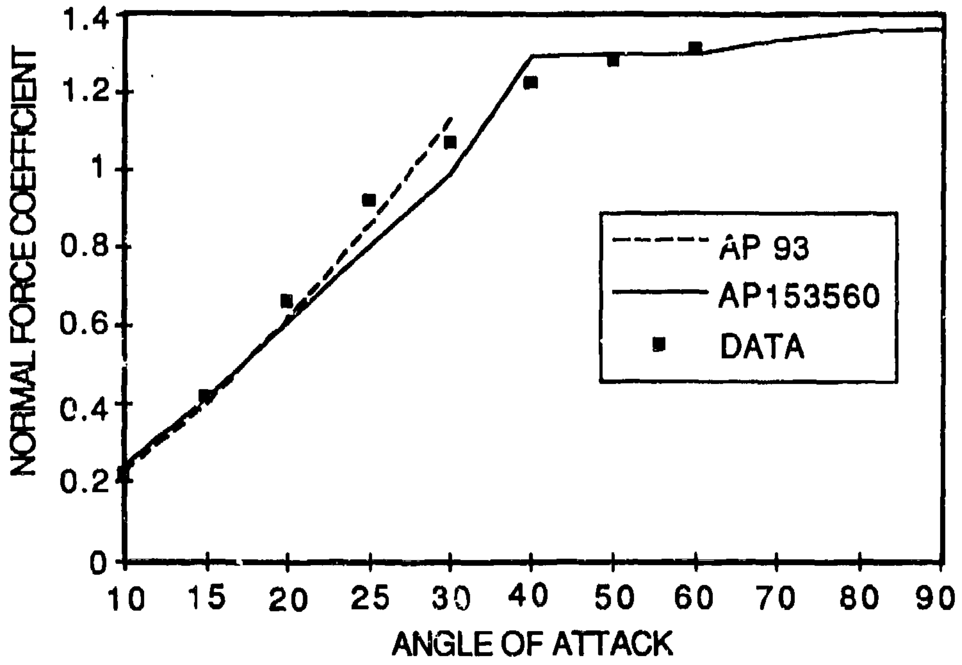

FIGURE 11. COMPARISON OF PREDICTED WING ALONE NORMAL FORCE COEFFICIENT WITH DATA (AR = 0.5, λ = .5, M_∞ = 0.8)

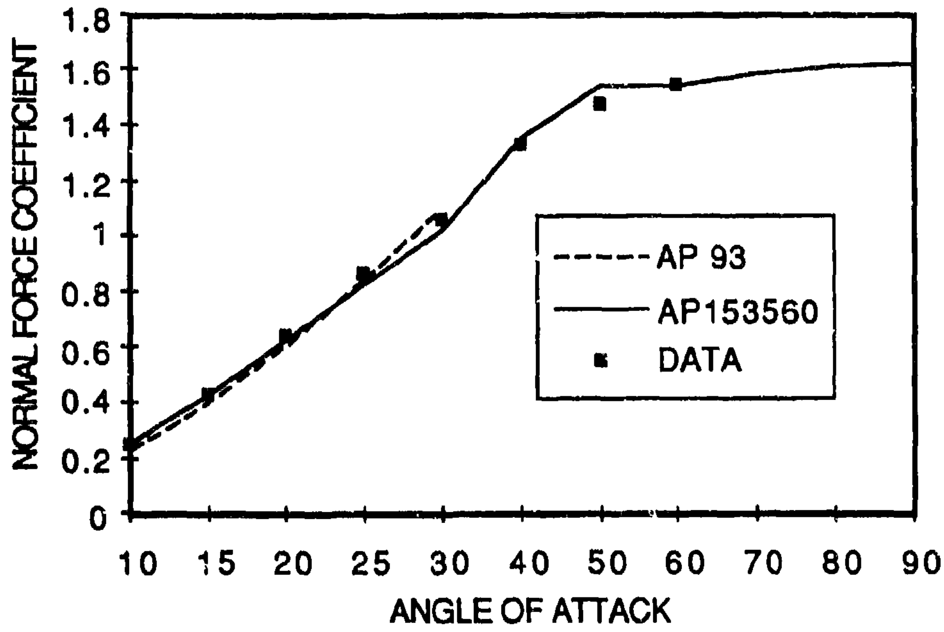

FIGURE 12. COMPARISON OF PREDICTED WING ALONE NORMAL FORCE COEFFICIENT WITH DATA (AR = 0.5, λ = .5, M_∞ = 1.2)

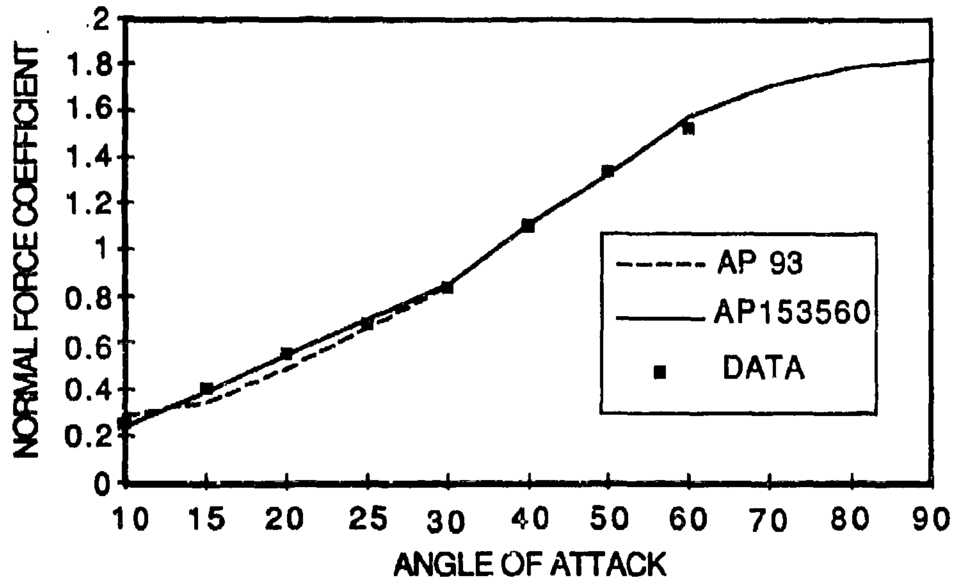

FIGURE 13. COMPARISON OF PREDICTED WING ALONE NORMAL FORCE COEFFICIENT WITH DATA (AR = 0.5, λ = .5, M_∞ = 2.0)

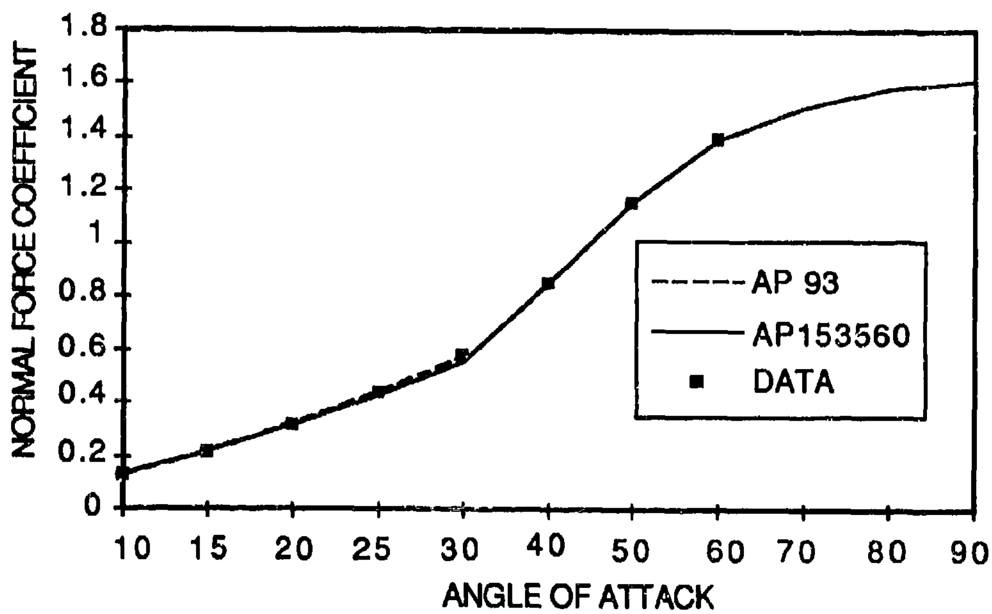

FIGURE 14. COMPARISON OF PREDICTED WING ALONE NORMAL FORCE COEFFICIENT WITH DATA (AR = 0.5, λ = .5, M_∞ = 4.5)

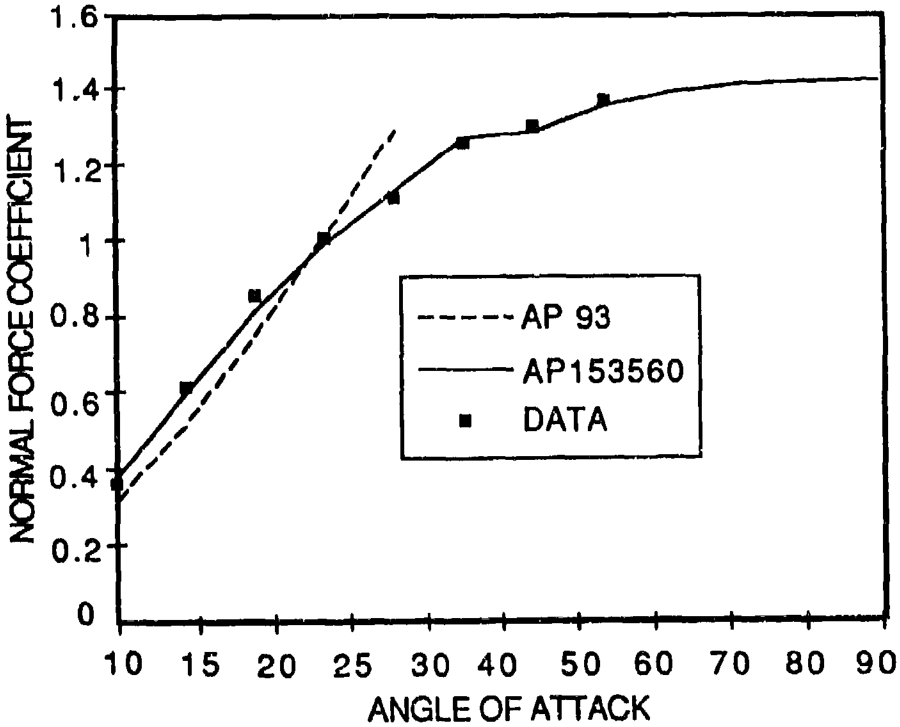

FIGURE 15. COMPARISON OF PREDICTED WING ALONE NORMAL FORCE COEFFICIENT WITH DATA (AR = 1.0, λ = .5, M_∞ = 0.8)

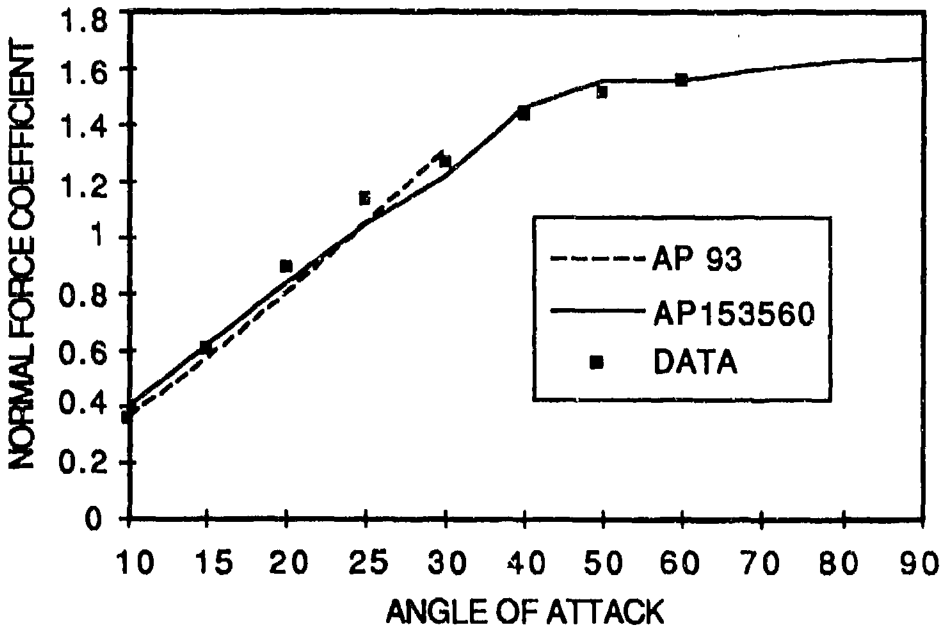

FIGURE 16. COMPARISON OF PREDICTED WING ALONE NORMAL FORCE COEFFICIENT WITH DATA (AR = 1.0, λ = .5, M_∞ = 1.2)

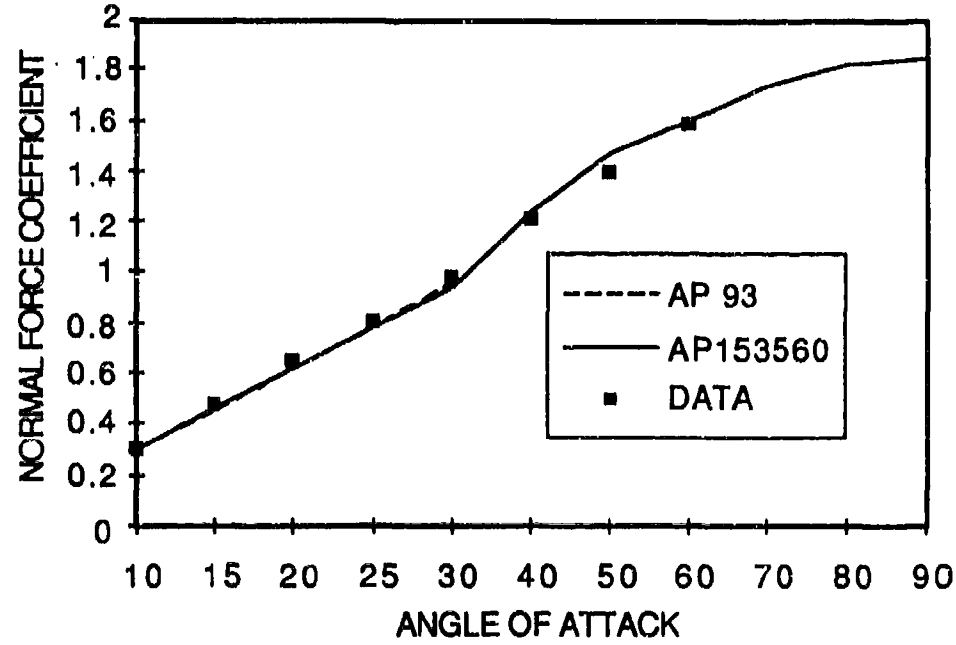

FIGURE 17. COMPARISON OF PREDICTED WING ALONE NORMAL FORCE COEFFICIENT WITH DATA (AR = 1.0, λ = .5, M_∞ = 2.0)

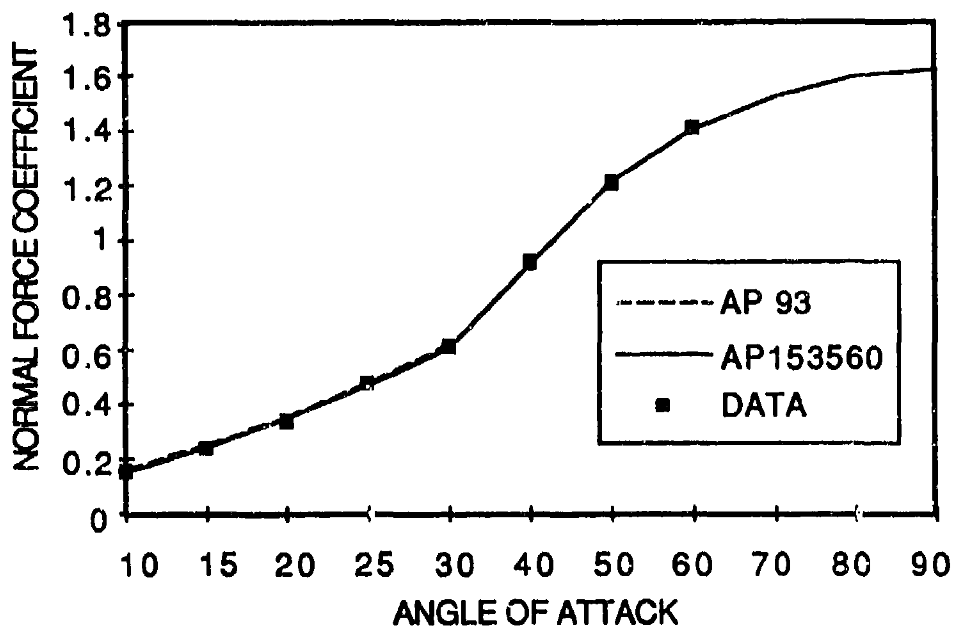

FIGURE 18. COMPARISON OF PREDICTED WING ALONE NORMAL FORCE COEFFICIENT WITH DATA (AR = 1.0, λ = .5, M_∞ = 4.5)

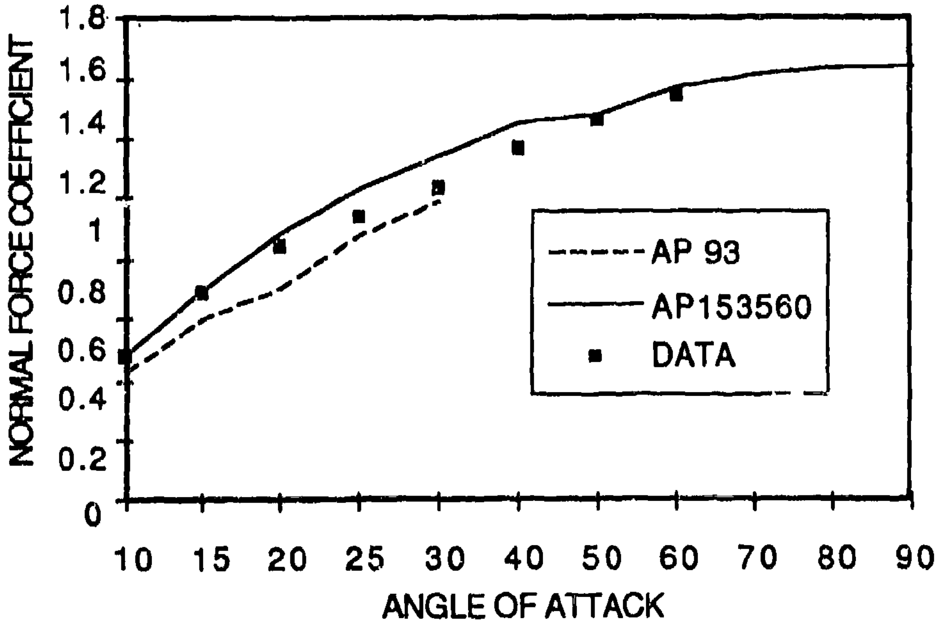

FIGURE 19. COMPARISON OF PREDICTED WING ALONE NORMAL FORCE COEFFICIENT WITH DATA (AR = 2.0, λ = .5, M_∞ = .8)

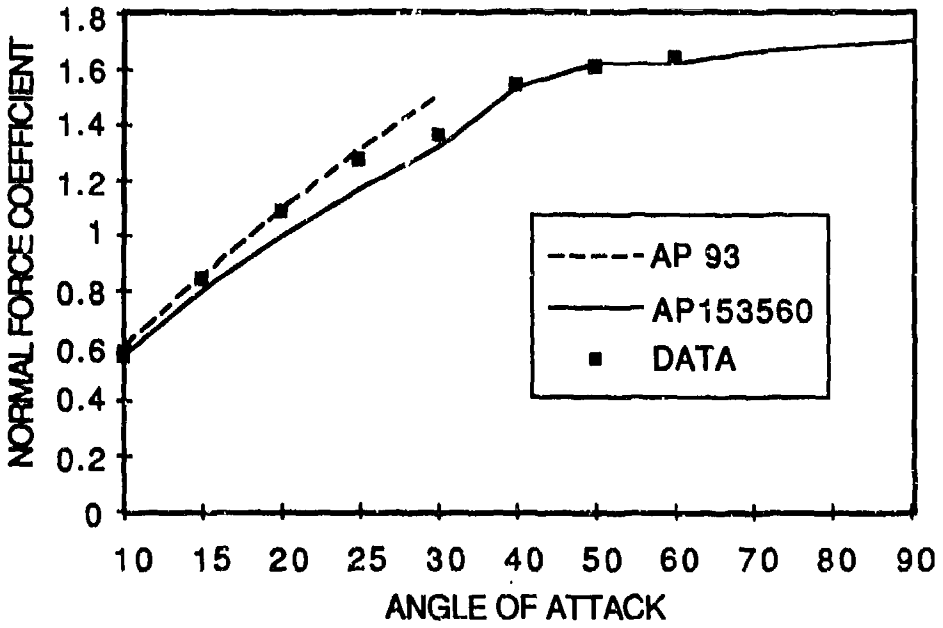

FIGURE 20. COMPARISON OF PREDICTED WING ALONE NORMAL FORCE COEFFICIENT WITH DATA (AR = 2.0, λ = .5, M_∞ = 1.2)

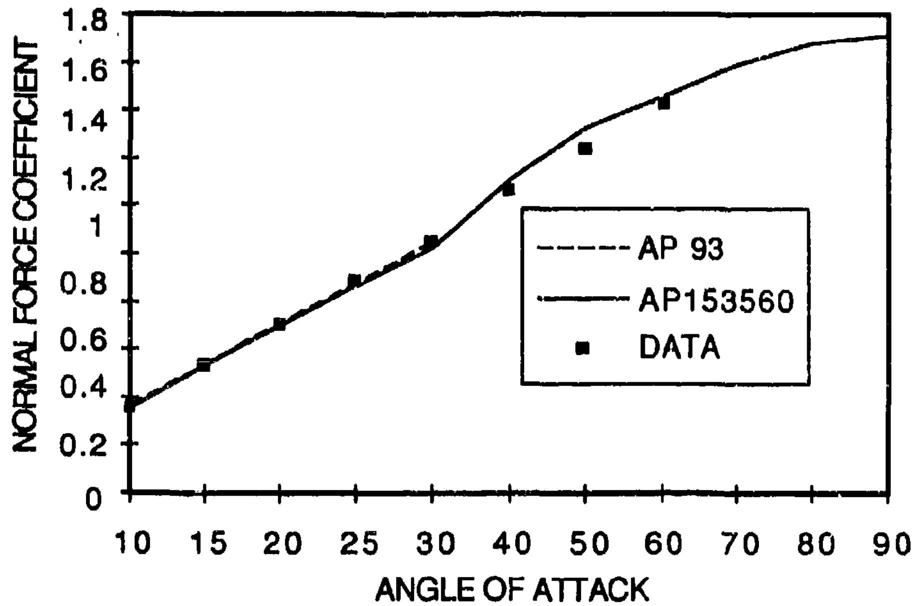

FIGURE 21. COMPARISON OF PREDICTED WING ALONE NORMAL FORCE COEFFICIENT WITH DATA (AR = 2.0, λ = .5, M_∞ = 2.0)

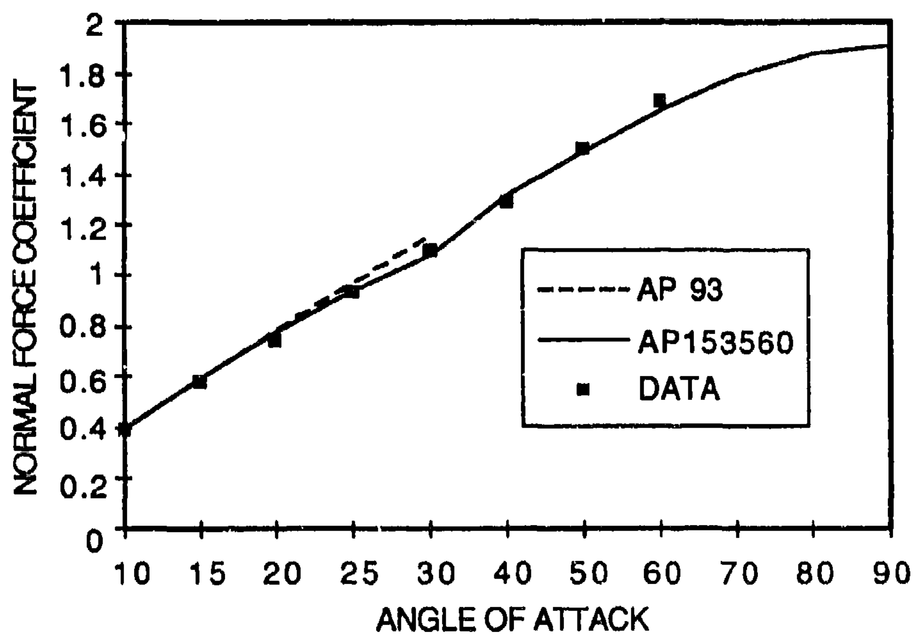

FIGURE 22. COMPARISON OF PREDICTED WING ALONE NORMAL FORCE COEFFICIENT WITH DATA (AR = 2.0, λ = .5, M_∞ = 4.5)

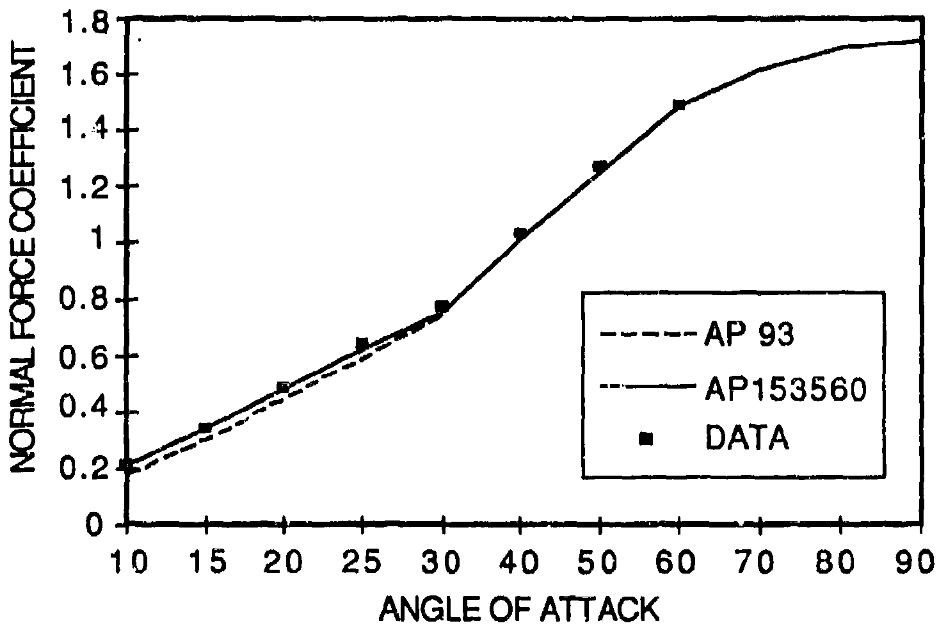

FIGURE 23. COMPARISON OF PREDICTED WING ALONE NORMAL FORCE COEFFICIENT WITH DATA (AR = 4.0, λ = .5, M_∞ = 2.0)

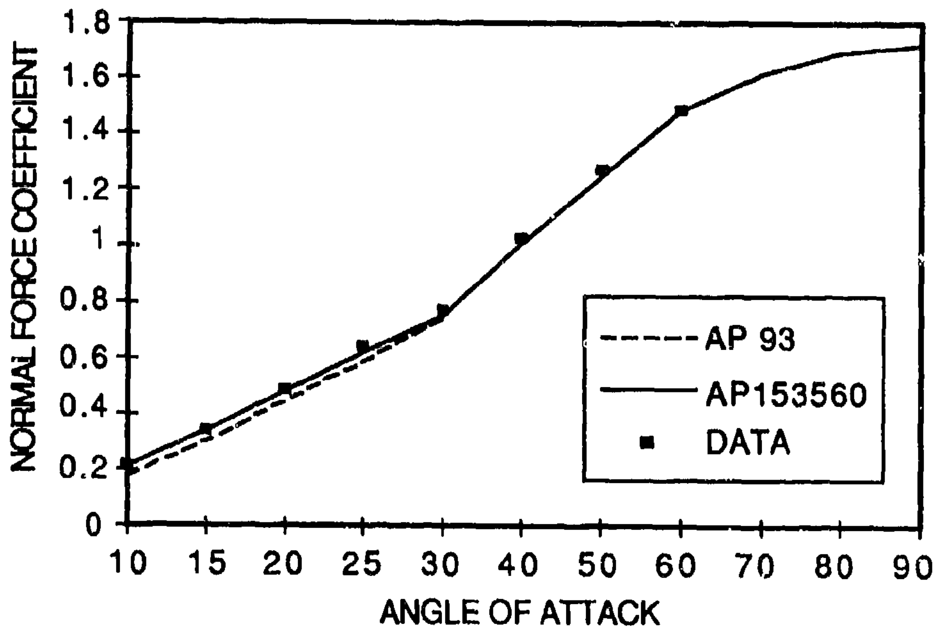

FIGURE 24. COMPARISON OF PREDICTED WING ALONE NORMAL FORCE COEFFICIENT WITH DATA (AR = 4.0, λ = .5, M_∞ = 4.5)

TABLE 1. VALUES OF $(C_N)_{\alpha = 15^\circ}$

Aspect Ratio	Taper Ratio	MACH NUMBER									
		0	0.6	0.8	1.0	1.2	1.6	2.0	3.0	4.5	≥6.0
≤0.5	0.0	.28	.29	.30	.32	.33	.33	.32	.24	.175	.16
	0.5	.39	.41	.415	.42	.43	.42	.39	.28	.22	.20
	1.0	.34	.34	.36	.40	.42	.44	.42	.31	.23	.22
1.0	0.0	.43	.44	.46	.49	.50	.46	.39	.28	.22	.22
	0.5	.47	.50	.60	.62	.625	.55	.46	.32	.24	.23
	1.0	.46	.48	.52	.58	.60	.55	.47	.36	.27	.26
2.0	0.0	.55	.64	.70	.72	.70	.60	.49	.34	.245	.24
	0.5	.56	.59	.70	.82	.80	.66	.53	.38	.29	.28
	1.0	.56	.60	.70	.80	.79	.62	.54	.40	.31	.29
≥4.0	0.0	.70	.71	.74	.86	.86	.69	.55	.40	.30	.28
	0.5	.74	.76	.78	.91	.92	.72	.59	.43	.34	.33
	1.0	.74	.76	.78	.91	.92	.72	.59	.43	.34	.33

TABLE 2. VALUES OF $(C_N)_{\alpha=20°}$

Aspect Ratio	Taper Ratio	MACH NUMBER									
		0	0.6	0.8	1.0	1.2	1.6	2.0	3.0	4.5	≥6.0
≤0.5	0.0	0.43	0.44	0.46	0.47	0.48	0.47	0.44	0.33	.28	.28
	0.5	.58	.60	.63	.66	.64	.60	.53	.40	.33	.33
	1.0	.51	.53	.56	.65	.64	.60	.54	.39	.33	.32
1.0	0.0	.67	.67	.68	.71	.70	.62	.52	.39	.31	.30
	0.5	.73	.75	.80	.87	.88	.77	.64	.45	.34	.33
	1.0	.73	.73	.75	.85	.82	.72	.63	.48	.38	.37
2.0	0.0	.85	.86	.90	.92	.88	.76	.63	.46	.37	.36
	0.5	.76	.78	.86	1.06	1.09	.87	.705	.51	.41	.40
	1.0	.75	.78	.84	.99	1.01	.83	.71	.55	.44	.43
≥4.0	0.0	.82	.82	.85	.96	1.03	.85	.71	.53	.45	.44
	0.5	.87	.88	.91	1.10	1.14	.92	.77	.58	.49	.48
	1.0	.87	.88	.91	1.10	1.14	.92	.77	.58	.49	.48

TABLE 3. VALUES OF $(C_N)_{\alpha=30°}$

Aspect Ratio	Taper Ratio	MACH NUMBER									
		0	0.6	0.8	1.0	1.2	1.6	2.2	3.0	4.5	≥6.0
≤0.5	0.0	.76	.78	.79	.805	.80	.77	.69	.59	.51	.48
	0.5	1.04	1.05	1.07	1.15	1.10	.96	0.8	.68	.56	.54
	1.0	.96	.98	1.01	1.01	1.04	.96	.85	.70	.59	.56
1.0	0.0	.98	.99	1.02	1.10	1.14	.94	.77	.66	.56	.54
	0.5	1.07	1.09	1.10	1.23	1.25	1.10	.91	.745	.61	.58
	1.0	1.02	1.02	1.05	1.14	1.19	1.11	.925	.79	.65	.64
2.0	0.0	1.01	1.02	1.07	1.31	1.28	1.10	.88	.72	.61	.585
	0.5	1.10	1.10	1.11	1.32	1.36	1.24	.97	.81	.69	.66
	1.0	1.04	1.05	1.08	1.32	1.28	1.18	1.0	.84	.72	.70
≥4.0	0.0	1.04	1.05	1.09	1.31	1.32	1.18	.94	.78	.66	.65
	0.5	1.11	1.11	1.12	1.34	1.40	1.28	1.02	.87	.76	.76
	1.0	1.11	1.11	1.12	1.34	1.40	1.28	1.02	.89	.80	.80

TABLE 4. VALUES OF $(C_N)_{\alpha=35°}$

Aspect Ratio	Taper Ratio	MACH NUMBER									
		0	0.6	0.8	1.0	1.2	1.6	2.0	3.0	4.5	≥6.0
≤0.5	0.0	.89	.91	.93	.95	.98	.95	.88	.72	.65	.63
	0.5	1.10	1.13	1.16	1.25	1.20	1.09	.98	.78	.70	.68
	1.0	1.06	1.08	1.13	1.16	1.19	1.12	1.00	.80	.70	.68
1.0	0.0	1.05	1.06	1.10	1.18	1.22	1.09	.97	.80	.70	.68
	0.5	1.12	1.15	1.22	1.30	1.36	1.20	1.09	.90	.76	.74
	1.0	1.10	1.11	1.16	1.23	1.34	1.20	1.09	.90	.78	.75
2.0	0.0	1.09	1.10	1.16	1.32	1.32	1.18	1.08	.93	.75	.73
	0.5	1.14	1.16	1.21	1.41	1.44	1.26	1.17	.97	.83	.81
	1.0	1.12	1.14	1.20	1.38	1.39	1.26	1.09	.97	.85	.83
≥4.0	0.0	1.13	1.14	1.20	1.33	1.38	1.23	1.10	.95	.81	.80
	0.5	1.17	1.18	1.25	1.44	1.48	1.30	1.21	1.02	.89	.88
	1.0	1.17	1.18	1.25	1.44	1.48	1.30	1.21	1.02	.89	.88

TABLE 5. VALUES OF $(C_N)_{\alpha = 45°}$

Aspect Ratio	Taper Ratio	MACH NUMBER									
		0	0.6	0.8	1.0	1.2	1.6	2.0	3.0	4.5	≥6.0
≤0.5	0.0	1.1	1.11	1.13	1.17	1.23	1.23	1.14	1.01	.94	.93
	0.5	1.20	1.23	1.26	1.35	1.40	1.30	1.21	1.08	1.01	1.00
	1.0	1.20	1.20	1.26	1.36	1.41	1.34	1.24	1.09	1.01	1.00
1.0	0.0	1.21	1.22	1.26	1.34	1.37	1.29	1.20	1.08	1.01	1.00
	0.5	1.24	1.25	1.29	1.42	1.48	1.43	1.31	1.17	1.09	1.08
	1.0	1.23	1.24	1.28	1.40	1.48	1.43	1.32	1.18	1.10	1.09
2.0	0.0	1.24	1.25	1.28	1.40	1.43	1.37	1.29	1.14	1.06	1.05
	0.5	1.28	1.29	1.31	1.55	1.57	1.46	1.38	1.23	1.15	1.15
	1.0	1.27	1.27	1.31	1.49	1.54	1.46	1.37	1.22	1.15	1.15
≥4.0	0.0	1.28	1.28	1.30	1.46	1.50	1.43	1.33	1.18	1.11	1.10
	0.5	1.32	1.33	1.35	1.60	1.64	1.48	1.38	1.24	1.17	1.17
	1.0	1.32	1.33	1.35	1.60	1.64	1.48	1.38	1.24	1.17	1.17

TABLE 6. VALUES OF $(C_N)_{\alpha=60°}$

Aspect Ratio	Taper Ratio	MACH NUMBER									
		0	0.6	0.8	1.0	1.2	1.6	2.2	3.0	4.5	≥6.0
≤0.5	0.0	1.22	1.23	1.28	1.40	1.48	1.52	1.48	1.4	1.34	1.34
	0.5	1.26	1.27	1.30	1.40	1.54	1.64	1.54	1.44	1.39	1.39
	1.0	1.26	1.27	1.30	1.40	1.51	1.58	1.54	1.46	1.40	1.40
1.0	0.0	1.30	1.31	1.33	1.47	1.53	1.57	1.51	1.43	1.38	1.38
	0.5	1.33	1.34	1.35	1.46	1.56	1.66	1.57	1.47	1.41	1.41
	1.0	1.33	1.34	1.35	1.44	1.58	1.66	1.60	1.50	1.44	1.44
2.0	0.0	1.31	1.32	1.34	1.48	1.58	1.64	1.53	1.44	1.40	1.40
	0.5	1.35	1.36	1.37	1.48	1.62	1.69	1.63	1.50	1.45	1.45
	1.0	1.35	1.36	1.37	1.48	1.63	1.69	1.63	1.54	1.46	1.46
≥4.0	0.0	1.32	1.33	1.37	1.50	1.64	1.66	1.56	1.47	1.42	1.42
	0.5	1.36	1.37	1.40	1.52	1.70	1.70	1.63	1.54	1.49	1.49
	1.0	1.36	1.37	1.40	1.52	1.70	1.70	1.63	1.54	1.49	1.49

TABLE 7. WING ALONE NORMAL FORCE COEFFICIENTS
($AR = 0.5$, $\lambda = 1.0$)

M	α	AP93	AP3060	AP2045	AP2060	AP153060	AP153560	DATA
.8	10	.218	.261	.232	.232	.204	0.209	.20
	15	.380	.446	.390	.391	.360	0.360	.37
	20	.574	.642	.560	.560	.552	0.534	.56
	25	.800	.835	.731	.729	.773	0.733	.82
	30	1.042	1.010	.892	.888	1.010	0.935	1.01
	40		1.274	1.162	1.147	1.340	1.300	1.21
	50		1.385	1.330	1.300	1.340	1.300	1.305
	60		1.340	1.388	1.340	1.340	1.300	1.34
	70					1.377	1.336	
	80					1.400	1.357	
	90					1.406	1.364	
1.2	10	.234	.261	.264	.264	.248	0.248	.24
	15	.403	.440	.446	.446	.420	0.420	.42
	20	.603	.631	.640	.640	.610	0.612	.64
	25	.830	.821	.833	.834	.807	0.811	.86
	30	1.081	1.001	1.014	1.015	1.000	1.007	1.04
	40		1.295	1.308	1.310	1.336	1.349	1.32
	50		1.471	1.478	1.481	1.520	1.520	1.46
	60		1.520	1.514	1.520	1.520	1.520	1.52
	70					1.562	1.562	
	80					1.587	1.587	
	90					1.595	1.595	
2.0	10	.217	.238	.234	.233	.257	0.257	.24
	15	.357	.392	.382	.381	.420	0.420	.385
	20	.518	.556	.540	.540	.586	0.584	.52
	25	.696	.723	.700	.703	.744	0.740	.68
	30	.888	.887	.854	.863	.887	0.879	.84
	40		1.182	1.128	1.157	1.122	1.106	1.14
	50		1.409	1.332	1.392	1.315	1.297	1.34
	60		1.554	1.455	1.553	1.554	1.553	1.54
	70					1.686	1.686	
	80					1.767	1.767	
	90					1.794	1.794	
4.5	10	.131	.150	.142	.143	.141	0.142	.13
	15	.219	.244	.230	.231	.230	0.230	.22
	20	.325	.350	.330	.330	.335	0.350	.33
	25	.441	.466	.444	.440	.456	0.443	.45
	30	.573	.590	.570	.561	.590	0.567	.57
	40		.858	.855	.828	.887	0.841	.85
	50		1.135	1.170	1.115	1.180	1.130	1.15
	60		1.400	1.491	1.400	1.400	1.400	1.39
	70					1.519	1.519	
	80					1.592	1.592	
	90					1.617	1.617	

TABLE 8. WING ALONE NORMAL FORCE COEFFICIENTS
(AR = 0.5, λ = 0.5)

M	α	AP93	AP3060	AP2045	AP2060	AP153060	AP153560	DATA
.8	10	.227	.274	.257	.256	.236	0.241	.22
	15	.402	.473	.439	.438	.415	0.415	.415
	20	.615	.684	.630	.651	.623	0.607	.66
	25	.861	.888	.814	.819	.846	0.804	.92
	30	1.135	1.070	.978	.991	1.070	0.992	1.07
	40		1.329	1.206	1.246	1.300	1.296	1.225
	50		1.405	1.269	1.351	1.300	1.300	1.28
	60		1.300	1.167	1.300	1.300	1.300	1.31
	70					1.336	1.336	
	80					1.357	1.357	
	90					1.364	1.364	
1.2	10	.228	.277	.260	.259	.246	0.251	.25
	15	.399	.477	.444	.443	.430	0.430	.43
	20	.605	.692	.640	.641	.642	0.627	.64
	25	.840	.904	.835	.838	.870	0.828	.86
	30	1.101	1.101	1.017	1.024	1.100	1.023	1.06
	40		1.406	1.305	1.327	1.504	1.351	1.32
	50		1.555	1.458	1.502	1.540	1.540	1.47
	60		1.540	1.468	1.540	1.540	1.540	1.54
	70					1.583	1.583	
	80					1.608	1.608	
	90					1.616	1.616	
2.0	10	.209	228	.230	.230	.239	0.239	.25
	15	.342	.374	.376	.373	.390	0.390	.40
	20	.494	.531	.530	.530	.548	0.549	.545
	25	.661	.693	.686	.692	.705	0.701	.68
	30	.841	.854	.837	.852	.854	0.846	.83
	40		1.152	1.102	1.151	1.118	1.103	1.10
	50		1.400	1.300	1.400	1.344	1.328	1.33
	60		1.574	1.412	1.573	1.573	1.573	1.52
	70					1.707	1.707	
	80					1.789	1.789	
	90					1.817	1.817.	
4.5	10	.130	.146	.144	.145	.137	0.137	.125
	15	.220	.234	.231	.232	.220	0.220	.21
	20	.327	.332	.330	.330	.318	0.318	.32
	25	.446	.441	.442	.438	.431	0.431	.44
	30	.578	.560	.568	.557	.560	0.559	.575
	40		.823	.853	.820	.852	0.850	.85
	50		1.107	1.173	1.105	1.152	1.150	1.15
	60		1.390	1.502	1.390	1.390	1.390	1.39
	70					1.508	1.508	
	80					1.581	1.581	
	90					1.606	1.605	

TABLE 9. WING ALONE NORMAL FORCE COEFFICIENTS
(AR = 0.5, λ = 0.0)

M	α	AP93	AP3060	AP2045	AP2060	AP153060	AP153560	DATA
.8	10	.195	.208	.194	.195	.177	0.178	.17
	15	.335	.347	.321	.323	.300	0.300	.305
	20	.500	.496	.460	.460	.447	0.441	.46
	25	.687	.646	.603	.600	.612	0.598	.64
	30	.894	.790	.746	.736	.790	0.764	.79
	40		1.036	1.013	.980	1.135	1.084	1.06
	50		1.203	1.232	1.165	1.280	1.280	1.20
	60		1.280	1.390	1.280	1.280	1.280	1.28
	70					1.315	1.315	
	80					1.336	1.336	
	90					1.343	1.343	
1.2	10	.193	.202	.198	.199	.189	0.189	.18
	15	.332	.339	.332	.333	.320	0.320	.32
	20	.495	.489	.480	.480	.469	0.471	.48
	25	.682	.645	.635	.633	.631	0.635	.64
	30	.887	.800	.793	.786	.800	0.808	.82
	40		1.087	1.094	1.073	1.128	1.143	1.11
	50		1.319	1.352	1.310	1.383	1.399	1.32
	60		1.480	1.550	1.480	1.480	1.480	1.48
	70					1.521	1.521	
	80					1.545	1.545	
	90					1.553	1.553	
2.0	10	.177	.179	.183	.183	.194	0.192	.185
	15	.301	.299	.305	.305	.320	0.320	.315
	20	.446	.431	.440	.440	.453	0.458	.44
	25	.609	.572	.582	.583	.587	0.601	.59
	30	.788	.717	.727	.731	.717	0.743	.72
	40		1.005	1.009	1.020	.960	1.011	1.00
	50		1.271	1.260	1.280	1.200	1.256	1.28
	60		1.494	1.459	1.493	1.493	1.493	1.50
	70					1.620	1.620	
	80					1.698	1.598	
	90					1.724	1.724	
4.5	10	.102	.127	.120	.122	.107	0.108	.10
	15	.188	.206	194	.195	.175	0.175	.17
	20	.287	.296	.280	.280	.263	0.261	.275
	25	.397	.397	.381	.377	.375	0.370	.385
	30	.523	.510	.499	.487	.510	0.500	.51
	40		.766	.779	.742	.831	0.812	.79
	50		1.050	1.111	1.034	1.151	1.131	1.09
	60		1.340	1.465	1.340	1.340	1.346	1.34
	70					1.454	1.454	
	80					1.524	1.524	
	90					1.547	1.547	

TABLE 10. WING ALONE NORMAL FORCE COEFFICIENTS
(AR = 1.0, λ = 1.0)

M	α	AP93	AP3060	AP2045	AP2060	AP153060	AP153560	DATA
.8	10	0.296	0.331	0.347	0.343	0.328	0.330	0.31
	15	0.468	0.523	0.551	0.547	0.520	0.520	0.52
	20	0.656	0.715	0.750	0.750	0.711	0.708	0.75
	25	0.858	0.894	0.927	0.939	0.891	0.883	0.93
	30	1.070	1.050	1.072	1.103	1.050	1.035	1.05
	40		1.270	1.227	1.325	1.278	1.254	1.185
	50		1.345	1.182	1.381	1.280	1.349	1.255
	60		1.280	0.954	1.280	1.280	1.350	1.28
	70					1.315	1.387	
	80					1.336	1.296	
	90					1.343	1.303	
1.2	10	0.342	0.379	0.386	0.384	0.383	0.383	0.375
	15	0.531	0.594	0.605	0.602	0.600	0.600	0.60
	20	0.732	0.807	0.820	0.820	0.814	0.814	0.84
	25	0.943	1.009	1.018	1.025	1.013	1.015	1.08
	30	1.162	1.190	1.190	1.209	1.190	1.192	1.24
	40		1.466	1.424	1.486	1.453	1.454	1.43
	50		1.606	1.493	1.619	1.584	1.578	1.54
	60		1.610	1.404	1.610	1.610	1.580	1.61
	70					1.654	1.614	
	80					1.680	1.639	
	90					1.689	1.647	
2.0	10	0.299	0.316	0.306	0.306	0.305	0.307	0.31
	15	0.458	0.487	0.468	0.468	0.470	0.470	0.48
	20	0.623	0.666	0.630	0.630	0.641	0.633	0.63
	25	0.793	0.827	0.788	0.789	0.815	0.793	0.79
	30	0.968	0.987	0.938	0.943	0.987	0.946	0.95
	40		1.267	1.206	1.221	1.303	1.223	1.21
	50		1.480	1.419	1.450	1.537	1.449	1.40
	60		1.620	1.569	1.620	1.620	1.620	1.57
	70					1.758	1.758	
	80					1.842	1.842	
	90					1.871	1.871	
4.5	10	0.161	0.171	0.165	0.166	0.166	0.167	0.17
	15	0.269	0.277	0.266	0.268	0.270	0.270	0.27
	20	0.389	0.393	0.380	0.380	0.386	0.395	0.38
	25	0.517	0.518	0.506	0.501	0.514	0.509	0.51
	30	0.656	0.650	0.642	0.630	0.650	0.642	0.64
	40		0.923	0.942	0.902	0.937	0.921	0.94
	50		1.193	1.260	1.179	1.215	1.197	1.21
	60		1.440	1.573	1.440	1.440	1.440	1.41
	70					1.562	1.562	
	80					1.638	1.638	
	90					1.663	1.663	

TABLE 11. WING ALONE NORMAL FORCE COEFFICIENTS
($AR = 1.0$, $\lambda = 0.5$)

M	α	AP93	AP3060	AP2045	AP2060	AP153060	AP153560	DATA
.8	10	0.318	0.339	0.363	0.357	0.383	0.377	0.36
	15	0.522	0.543	0.584	0.578	0.610	0.600	0.61
	20	0.754	0.748	0.800	0.800	0.819	0.812	0.85
	25	1.010	0.940	0.992	1.008	0.989	0.992	1.00
	30	1.287	1.102	1.147	1.188	1.110	1.130	1.11
	40		1.350	1.300	1.431	1.208	1.267	1.25
	50		1.432	1.219	1.486	1.210	1.282	1.29
	60		1.360	0.924	1.360	1.360	1.350	1.36
	70					1.398	1.363	
	80					1.420	1.385	
	90					1.427	1.392	
1.2	10	0.365	0.392	0.416	0.411	0.386	0.399	0.36
	15	0.577	0.613	0.656	0.652	0.605	0.625	0.61
	20	0.808	0.833	0.890	0.890	0.824	0.845	0.90
	25	1.055	1.038	1.099	1.112	1.032	1.047	1.14
	30	1.316	1.220	1.271	1.305	1.220	1.221	1.27
	40		1.485	1.466	1.573	1.503	1.462	1.44
	50		1.597	1.436	1.656	1.560	1.560	1.52
	60		1.560	1.202	1.560	1.560	1.560	1.56
	70					1.603	1.603	
	80					1.628	1.628	
	90					1.637	1.637	
2.0	10	0.300	0.316	0.313	0.312	0.300	0.302	0.30
	15	0.457	0.485	0.477	0.476	0.460	0.460	0.47
	20	0.618	0.654	0.640	0.640	0.627	0.620	0.645
	25	0.782	0.818	0.797	0.800	0.800	0.781	0.80
	30	0.949	0.973	0.946	0.953	0.973	0.938	0.97
	40		1.247	1.204	1.226	1.300	1.231	1.20
	50		1.458	1.399	1.444	1.541	1.466	1.39
	60		1.600	1.526	1.600	1.600	1.600	1.58
	70					1.736	1.736	
	80					1.820	1.820	
	90					1.848	1.848	
4.5	10	0.155	0.167	0.152	0.156	0.151	0.151	0.145
	15	0.244	0.264	0.240	0.243	0.240	0.240	0.235
	20	0.350	0.371	0.340	0.340	0.346	0.345	0.335
	25	0.475	0.487	0.456	0.446	0.469	0.468	0.47
	30	0.616	0.610	0.590	0.563	0.610	0.607	0.61
	40		0.873	0.908	0.825	0.925	0.919	0.92
	50		1.147	1.284	1.114	1.227	1.221	1.21
	60		1.410	1.687	1.410	1.410	1.410	1.41
	70					1.530	1.530	
	80					1.603	1.603	
	90					1.628	1.628	

TABLE 12. WING ALONE NORMAL FORCE COEFFICIENTS
($AR = 1.0, \lambda = 0.0$)

M	α	AP93	AP3060	AP2045	AP2060	AP153060	AP153560	DATA
.8	10	0.283	0.322	0.310	0.309	0.284	0.291	0.27
	15	0.457	0.517	0.495	0.494	0.460	0.460	0.42
	20	0.650	0.715	0.680	0.680	0.655	0.634	0.68
	25	0.860	0.903	0.854	0.858	0.862	0.803	0.91
	30	1.084	1.070	1.008	1.017	1.070	0.961	1.07
	40		1.313	1.230	1.259	1.433	1.215	1.24
	50		1.409	1.314	1.373	1.360	1.330	1.32
	60		1.360	1.264	1.360	1.360	1.330	1.36
	70					1.398	1.398	
	80					1.420	1.420	
	90					1.427	1.427	
1.2	10	0.302	0.344	0.325	0.323	0.311	0.316	0.30
	15	0.481	0.551	0.512	0.511	0.500	0.500	0.495
	20	0.676	0.760	0.700	0.700	0.707	0.690	0.70
	25	0.887	0.960	0.879	0.882	0.923	0.879	0.94
	30	1.110	1.140	1.040	1.050	1.140	1.058	1.10
	40		1.413	1.289	1.320	1.520	1.358	1.31
	50		1.543	1.419	1.481	1.530	1.530	1.43
	60		1.530	1.428	1.530	1.530	1.530	1.52
	70					1.572	1.572	
	80					1.597	1.597	
	90					1.605	1.605	
2.0	10	0.247	0.257	0.250	0.250	0.252	0.252	0.25
	15	0.379	0.397	0.383	0.383	0.390	0.390	0.39
	20	0.517	0.540	0.520	0.520	0.533	0.533	0.53
	25	0.659	0.684	0.659	0.658	0.680	0.679	0.68
	30	0.805	0.827	0.798	0.796	0.827	0.826	0.82
	40		1.097	1.070	1.066	1.111	1.109	1.11
	50		1.336	1.323	1.315	1.358	1.355	1.33
	60		1.530	1.544	1.530	1.530	1.530	1.53
	70					1.660	1.660	
	80					1.740	1.740	
	90					1.767	1.767	
4.5	10	0.150	0.162	0.147	0.150	0.143	0.143	0.13
	15	0.228	0.250	0.223	0.227	0.220	0.220	0.22
	20	0.328	0.344	0.310	0.310	0.313	0.312	0.31
	25	0.443	0.447	0.412	0.403	0.426	0.422	0.425
	30	0.575	0.560	0.532	0.509	0.560	0.552	0.56
	40		0.812	0.832	0.759	0.874	0.859	0.85
	50		1.092	1.204	1.057	1.190	1.173	1.15
	60		1.380	1.621	1.380	1.380	1.380	1.38
	70					1.497	1.497	
	80					1.569	1.569	
	90					1.380	1.594	

TABLE 13. WING ALONE NORMAL FORCE COEFFICIENTS
($AR = 2.0$, $\lambda = 1.0$)

M	α	AP93	AP3060	AP2045	AP2060	AP153060	AP153560	DATA
2.0	10	0.348	0.361	0.356	0.355	0.357	0.362	0.375
	15	0.527	0.546	0.536	0.535	0.540	0.540	0.545
	20	0.708	0.727	0.710	0.710	0.721	0.705	0.71
	25	0.892	0.900	0.874	0.878	0.895	0.852	0.87
	30	1.077	1.060	1.024	1.034	1.060	0.980	1.02
	40		1.333	1.274	1.306	1.346	1.187	1.26
	50		1.530	1.446	1.512	1.550	1.377	1.44
	60		1.650	1.542	1.650	1.650	1.650	1.65
	70					1.790	1.790	
	80					1.876	1.876	
	90					1.905	1.905	
4.5	10	0.181	0.191	0.190	0.190	0.190	0.191	0.18
	15	0.300	0.311	0.309	0.310	0.310	0.310	0.30
	20	0.435	0.442	0.440	0.440	0.441	0.439	0.425
	25	0.578	0.580	0.579	0.577	0.579	0.575	0.595
	30	0.725	0.720	0.722	0.717	0.720	0.712	0.72
	40			1.011	0.994	0.999	0.984	1.00
	50			1.282	1.247	1.253	1.237	1.26
	60			1.517	1.460	1.460	1.460	1.46
	70					1.584	1.584	
	80					1.660	1.660	
	90					1.686	1.686	
	10							
	15							
	20							
	25							
	30							
	40							
	50							
	60							
	70							
	80							
	90							
	10							
	15							
	20							
	25							
	30							
	40							
	50							
	60							
	70							
	80							
	90							

TABLE 14. WING ALONE NORMAL FORCE COEFFICIENTS
($AR = 2.0$, $\lambda = 0.5$)

M	α	AP93	AP3060	AP2045	AP2060	AP153060	AP153560	DATA
.8	10	0.430	0.456	0.463	0.459	0.485	0.485	0.48
	15	0.603	0.656	0.665	0.661	0.700	0.700	0.69
	20	0.704	0.833	0.840	0.840	0.879	0.885	0.84
	25	0.878	0.984	0.984	0.994	1.016	1.032	0.94
	30	0.985	1.110	1.093	1.121	1.110	1.140	1.03
	40		1.282	1.206	1.293	1.189	1.250	1.16
	50		1.353	1.182	1.360	1.208	1.282	1.26
	60		1.340	1.049	1.340	1.340	1.370	1.34
	70					1.377	1.408	
	80					1.399	1.430	
	90					1.406	1.437	
1.2	10	0.599	0.586	0.608	0.604	0.593	0.570	0.56
	15	0.860	0.830	0.867	0.864	0.840	0.800	0.84
	20	1.098	1.039	1.090	1.090	1.050	1.000	1.09
	25	1.315	1.216	1.272	1.281	1.223	1.172	1.27
	30	1.515	1.360	1.411	1.436	1.360	1.320	1.36
	40		1.559	1.559	1.637	1.536	1.536	1.54
	50		1.651	1.543	1.703	1.616	1.620	1.61
	60		1.660	1.398	1.660	1.660	1.620	1.64
	70					1.706	1.665	
	80					1.733	1.691	
	90					1.742	1.700	
2.0	10	0.358	0.372	0.360	0.360	0.354	0.357	0.355
	15	0.532	0.556	0.533	0.533	0.530	0.530	0.535
	20	0.704	0.734	0.700	0.700	0.707	0.699	0.705
	25	0.874	0.903	0.858	0.859	0.885	0.864	0.880
	30	1.042	1.060	1.006	1.008	1.060	1.022	1.045
	40		1.329	1.268	1.275	1.383	1.306	1.260
	50		1.529	1.478	1.494	1.615	1.528	1.440
	60		1.660	1.635	1.660	1.660	1.650	1.630
	70					1.801	1.790	
	80					1.888	1.876	
	90					1.917	1.905	
4.5	10	0.171	0.187	0.180	0.182	0.180	0.180	0.190
	15	0.288	0.301	0.289	0.291	0.290	0.290	0.290
	20	0.422	0.424	0.410	0.410	0.413	0.412	0.420
	25	0.559	0.555	0.542	0.536	0.547	0.545	0.550
	30	0.704	0.690	0.684	0.668	0.690	0.685	0.690
	40		0.962	0.990	0.940	0.985	0.975	0.980
	50		1.222	1.310	1.207	1.257	1.246	1.270
	60		1.450	1.619	1.450	1.450	1.450	1.450
	70					1.573	1.573	
	80					1.649	1.649	
	90					1.674	1.674	

TABLE 15. WING ALONE NORMAL FORCE COEFFICIENTS
(AR = 2.0, λ = 0.0)

M	α	AP93	AP3060	AP2045	AP2060	AP153060	AP153560	DATA
2.0	10	0.368	0.355	0.339	0.340	0.336	0.337	0.320
	15	0.548	0.518	0.489	0.490	0.490	0.490	0.480
	20	0.725	0.672	0.630	0.630	0.643	0.639	0.630
	25	0.899	0.817	0.766	0.763	0.797	0.787	0.780
	30	1.072	0.953	0.899	0.891	0.953	0.934	0.925
	40		1.199	1.160	1.135	1.258	1.220	1.190
	50		1.409	1.418	1.366	1.500	1.455	1.390
	60		1.580	1.666	1.580	1.580	1.567	1.580
	70					1.714	1.700	
	80					1.797	1.781	
	90					1.824	1.809	
4.5	10	0.162	0.174	0.169	0.171	0.156	0.156	0.155
	15	0.259	0.272	0.264	0.267	0.245	0.245	0.250
	20	0.380	0.377	0.370	0.370	0.349	0.348	0.350
	25	0.530	0.490	0.487	0.481	0.471	0.467	0.465
	30	0.696	0.610	0.615	0.599	0.610	0.602	0.605
	40		0.864	0.903	0.852	0.920	0.906	0.900
	50		1.127	1.222	1.119	1.215	1.204	1.200
	60		1.380	1.549	1.380	1.380	1.400	1.380
	70					1.497	1.519	
	80					1.569	1.592	
	90					1.594	1.617	
	10							
	15							
	20							
	25							
	30							
	40							
	50							
	60							
	70							
	80							
	90							
	10							
	15							
	20							
	25							
	30							
	40							
	50							
	60							
	70							
	80							
	90							

TABLE 16. WING ALONE NORMAL FORCE COEFFICIENTS
($AR = 4.0$, $\lambda = 0.5$)

M	α	AP93	AP3060	AP2045	AP2060	AP153060	AP153560	DATA
2.0	10	0.398	0.389	0.394	0.392	0.396	0.396	0.390
	15	0.592	0.578	0.588	0.585	0.590	0.590	0.580
	20	0.784	0.760	0.770	0.770	0.772	0.772	0.745
	25	0.973	0.931	0.936	0.943	0.939	0.937	0.930
	30	1.160	1.087	1.083	1.101	1.087	1.083	1.100
	40		1.349	1.306	1.364	1.325	1.318	1.290
	50		1.538	1.429	1.548	1.500	1.493	1.500
	60		1.630	1.459	1.653	1.653	1.653	1.690
	70					1.794	1.794	
	80					1.880	1.880	
	90					1.909	1.909	
4.5	10	0.181	0.202	0.210	0.210	0.209	0.209	0.210
	15	0.304	0.330	0.345	0.344	0.340	0.340	0.340
	20	0.445	0.469	0.490	0.490	0.479	0.479	0.485
	25	0.590	0.614	0.638	0.641	0.621	0.619	0.640
	30	0.743	0.760	0.784	0.791	0.760	0.757	0.770
	40		1.042	1.054	1.075	1.022	1.016	1.030
	50		1.292	1.270	1.313	1.260	1.253	1.270
	60		1.490	1.420	1.490	1.490	1.490	1.490
	70					1.617	1.617	
	80					1.694	1.694	
	90					1.720	1.720	
	10							
	15							
	20							
	25							
	30							
	40							
	50							
	60							
	70							
	80							
	90							
	10							
	15							
	20							
	25							
	30							
	40							
	50							
	60							
	70							
	80							
	90							

TABLE 17. PERCENT ERROR VALUES FOR ASPECT RATIO 0.5

λ	M	AP93	AP3060	AP2045	AP2060	AP153060	AP153560
1.0	0.8	4.68	17.62(14.22)	10.33(8.41)	10.56(8.55)	3.03(4.58)	6.50(5.77)
	1.2	4.14	5.22 (4.19)	5.65(4.50)	5.61(4.47)	4.14(3.60)	3.80(3.43)
	2.0	6.12	4.97 (4.63)	2.58(2.83)	3.01(2.89)	9.09(7.23)	8.80(7.10)
	4.5	1.19	7.10 (7.02)	4.50(4.43)	5.04(4.24)	4.57(4.03)	5.42(4.36)
0.5	0.8	5.36	12.86(11.16)	10.48(8.87)	9.88(8.09)	5.48(4.88)	8.56(7.10)
	1.2	5.97	8.32(7.26)	3.23(3.07)	2.89(2.42)	1.91(5.41)	1.56(2.71)
	2.0	10.75	5.24((4.97)	4.76(4.60)	5.09(4.85)	3.10(2.83)	2.78(2.53)
	4.5	3.10	9.25(7.51)	8.16(7.08)	8.85(7.24)	4.99(3.95)	5.02(3.97)
0.0	0.8	11.14	12.22(9.69)	7.59(6.97)	8.26(7.12)	3.02(4.19)	4.38(4.65)
	1.2	6.08	6.25(4.99)	4.98(4.39)	5.35(4.40)	2.83(2.84)	2.44(3.06)
	2.0	5.22	3.19(2.54)	1.64(1.74)	1.79(1.59)	2.57(3.31)	3.07(2.55)
	4.5	5.49	15.79(12.59)	11.01(9.34)	12.05(9.93)	4.06(4.20)	4.66(4.03)

TABLE 18. PERCENT ERROR VALUES FOR ASPECT RATIO 1.0

λ	M	AP93	AP3060	AP2045	AP2060	AP153060	AP153560
1.0	0.8	8.24	4.06(4.82)	6.07(10.49)	5.75(7.13)	4.02(4.26)	4.88(4.48)
	1.2	10.70	3.92(3.55)	3.60(5.46)	2.95(3.25)	3.71(3.16)	3.57(3.02)
	2.0	2.82	3.62(4.04)	1.32(1.16)	1.35(2.01)	2.66(5.01)	1.16(1.91)
	4.5	2.85	2.23(2.07)	1.63(4.54)	1.45(2.17)	1.39(1.34)	1.89(1.84)
0.5	0.8	12.05	8.20(8.07)	3.61(11.91)	3.80(8.01)	3.34(3.64)	2.49(2.43)
	1.2	6.35	6.74(5.72)	7.94(10.45)	7.29(7.33)	6.73(5.62)	6.96(5.61)
	2.0	2.68	3.05(3.30)	2.32(2.20)	2.04(2.29)	1.58(5.04)	2.65(3.04)
	4.5	4.10	10.08(8.37)	3.16(7.69)	5.53(6.34)	2.44(2.00)	2.40(1.92)
0.0	0.8	5.53	13.61(11.22)	11.07(9.11)	10.74(8.63)	5.62(5.71)	9.35(7.47)
	1.2	3.26	9.36(8.38)	5.48(4.86)	5.07(4.22)	2.49(6.04)	4.19(4.37)
	2.0	2.40	1.72(1.43)	2.18(2.17)	2.24(2.31)	0.63(0.90)	0.60(0.82)
	4.5	7.78	13.74(11.11)	6.50(8.25)	8.50(8.22)	4.49(3.82)	4.62(3.74)

TABLE 19. PERCENT ERROR VALUES FOR ASPECT RATIO 2.0

λ	M	AP93	AP3060	AP2045	AP2060	AP153060	AP153560
1.0	2.0	4.45	3.04(3.85)	2.36(2.99)	2.67(3.03)	3.15(4.38)	2.58(3.28)
	4.5	1.72	3.81(3.02)	3.37(3.09)	3.60(2.88)	3.59(2.84)	3.74(3.07)
0.5	0.8	10.85	5.13(6.08)	4.10(8.72)	5.42(6.51)	5.49(4.66)	6.14(6.92)
	1.2	6.28	3.58(3.02)	4.40(6.47)	4.52(4.71)	3.56(2.85)	5.68(4.57)
	2.0	0.54	3.54(3.62)	2.12(1.94)	2.05(2.22)	0.79(5.58)	1.35(2.77)
	4.5	4.64	1.92(2.12)	2.78(4.80)	2.84(3.08)	2.53(2.04)	2.54(2.11)
0.0	2.0	15.07	7.10(5.64)	3.13(3.33)	3.60(3.33)	3.23(4.29)	2.92(2.99)
	4.5	10.26	7.86(6.72)	5.81(6.33)	6.23(5.79)	1.18(1.29)	1.09(0.89)

TABLE 20. PERCENT ERROR VALUES FOR ASPECT RATIO 4.0

λ	M	AP93	AP3060	AP2045	AP2060	AP153060	AP153560
0.5	2.0	4.17	1.06(2.38)	1.87(5.32)	1.71(2.79)	2.07(2.05)	2.06(1.98)
	4.5	9.49	3.19(2.63)	1.18(2.08)	1.45(2.25)	1.58(1.31)	1.74(1.52)

TABLE 21. AVERAGED ERRORS FOR EACH ASPECT RATIO

AR	AP93	AP3060	AP2045	AP2060	AP153060	AP153560
0.5	5.77	9.00(7.56)	6.24(5.52)	6.53(5.48)	4.06(4.25)	4.75(4.27)
1.0	5.73	6.69(6.01)	4.57(6.52)	4.72(4.29)	3.26(3.88)	3.73(3.39)
2.0	6.73	4.50(4.26)	3.51(4.71)	3.87(3.94)	2.94(3.49)	3.26(3.32)
4.0	6.83	2.17(2.50)	1.52(3.70)	1.58(2.52)	1.82(1.68)	1.90(1.75)

TABLE 22. GLOBAL ERRORS FOR EACH METHOD

AP93	6.04
AP3060	6.72(5.94)
AP2045	4.73(5.58)
AP2060	4.97(4.52)
AP153060	3.38(3.79)
AP153560	3.87(3.59)

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SYMBOLS AND DEFINITIONS

Symbol	Definition
a_0, a_1, a_2, a_3, a_4	Coefficients used in definition of fourth-order nonlinear representation of wing alone normal force coefficient
A_{ref}, A_w	Reference and wing planform area, respectively
AOA	Angle of Attack
APC	Aeroprediction Code
AP81, AP93	1981 and 1993 versions of Aeroprediction Code, respectively
AR	Aspect ratio $= b^2/A_W$
b	Wing Span
C_N	Normal Force Coefficient
C_{N_L}	Linear component of normal force coefficient
$C_{N_{NL}}$	Nonlinear component of normal force coefficient
C_{N_w}	Wing alone normal force coefficient
C_{N_α}	Normal force coefficient derivative
C_r	Wing root chord
C_t	Wing tip chord
K_1	Constant used to define nonlinear normal force coefficient used in AP93
M_∞	Freestream Mach Number
M_N	Normal Mach Number $= M_\infty \sin\alpha$

SYMBOLS AND DEFINITIONS (Continued)

Symbol	Definition
α	Angle of attack (degrees or radians)
α_w	Local angle of attack of wing with respect to freestream = $\alpha + \delta$
α^*	$\alpha - \pi/2$
Π	$180^\circ = 3.14$ radians
δ	Wing deflection (degrees or radians)
λ	Taper ratio of wing planform = C_t/C_r

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A new semiempirical method has been developed to estimate wing alone aerodynamics at all Mach numbers and angles of attack (AOA) encountered in flight. The method utilizes the slender body or linearized theories at low AOA and several wing alone data bases at higher AOA. In areas where data is not available, extrapolations and interpolations are used with existing data. The new method is shown to be more accurate than the second-order technique developed for the 1993 version of the NSWCDD Aeroprediction Code (AP93) over the AOA range of 0 to 30 deg where that technique is applicable. More importantly, however, is the fact that the new method allows AOA to 180 deg. As a result, this new wing alone method forms the first step in expanding the AP93 to higher AOA than 30 deg.

14. SUBJECT TERMS

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